Final author response to anonymous referee #1

Bg-2014-478: "Long term effects on regional European boreal climate due to structural vegetation changes" by J. H. Rydsaa, F. Stordal, and L. M. Tallaksen

The referee comments are answered in the following way:

I. the referee comment in italics
II. author response comments
III. reference to corresponding changes in the manuscript.

General comments:

Comment 1

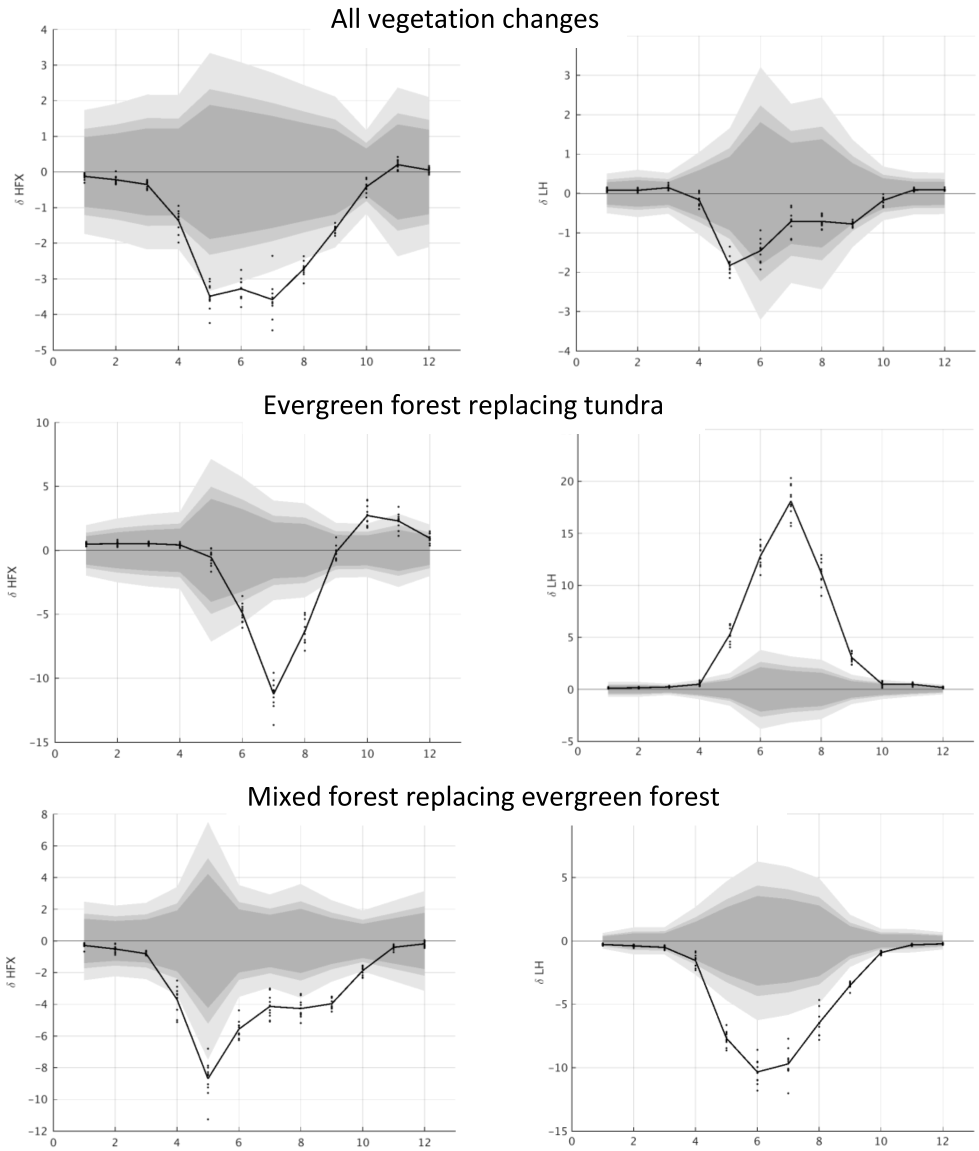
I. "*The authors describe two WRF experiments to demonstrate the effects of northward shifts of boreal vegetation due to anticipated climate change. The experiments include the structural changes in high latitude ecosystems, which result in changes in soil moisture properties and heat fluxes.*"
II. We greatly appreciate the referee taking time to read and comment our manuscript. We have revised the manuscript in accordance with the referee's constructive comments and suggestions.

Specific comments:

Comment 1

I. "*Are 10 years sufficient for statistical analysis? Is it possible to either increase the number of years (e.g. to 2001-2012) to have at least twelve annual samples, or to analyze seasonal data with taking all months into account (to have at least 30 months per season) and perform some sort of statistical analysis to show the significance of the results (see also technical comment 11)?*"
II. The referee makes a good point, and we agree that statistical significance of the results would greatly improve the manuscript. We have added a statistical analysis to be able to comment on the significance of the results on a seasonal scale. A Student's t-test is applied to the 10 year averages, and annual mean figures updated accordingly. For the seasonal analysis, we have applied a similar approach to what the referee suggested.

As the separate monthly values of surface fluxes within each season are not independent of each other, due to temporal autocorrelation in the form of soil moisture etc., in our opinion using 30 months as the population of an analysis might yield biased results. Instead, we have computed monthly mean confidence intervals based on Student's t-test statistics. Monthly means are computed for each area with vegetation changes. Plotting the difference compared to the control simulation with the normalized confidence interval indicates the seasonal statistical significance of monthly means of each area. Each monthly mean outside the confidence interval (chosen here as 95%) is significantly different from the control run mean (i.e. have a 5% chance of passing the interval by chance). Below we have included a figure with results that show the seasonal significance of monthly mean sensible and latent heat flux for different areas of vegetation changes (gray shadings indicate 90, 95 and 99 % conf. intervals). It is clear that the area averaged monthly mean anomalies are only significant in the summer months (May through September), when taking into account all areas with vegetation changes together (upper, left panel). Breaking it up and looking at the areas separately, the area where the tundra pft is changed for the evergreen forest pft (middle, left panel), significant changes are seen in June, July and August, and for the area with mixed forest northward migration, the period from April through October, shows significantly different means from the control simulation (lower left panel). For the latent heat flux, similar results show significant changes during the summer months for each area with forest expansion (middle and lower right panels), and only for May when all areas are averaged together (upper, right). Black dots indicate the ten monthly values.



The manuscript is rewritten in accordance with these findings (See reference to changes in the results and discussion section in technical comments number 11). To avoid excessive figures in the manuscript, the statistical significance of monthly mean anomalies is presented in revised version of Figure 10, where significant results are indicated by circles (as explained in the new figure caption).

Comment 2

I. "*Especially sensible heat flux seems to have a strong annual cycle with observed increases especially during the growing season (Beringer et al., 2005, their Fig. 7) and warmer daytime (Beringer et al., 2001, 2005). Over Norway and Sweden, previous studies found simulated decreases in Sept.-Feb. and increases otherwise (see Snyder and Liess (2014, Climate Dyn. 42, 487–503, their Fig. 6), Jeong et al., (2014,* *Environ. Res. Lett. 9, 094007, doi:10.1088/1748-9326/9/9/094007, their Table 1), and Jeong et al. (2011, Climate Dyn. 37, 821-833, their Fig. 5). The present study finds a decrease in sensible heat flux with resulting decrease in 2m temperature. This should be discussed and maybe related to possible changes in simulated precipitation (see also technical comments 15, 18, and 21).”*

II. The opposite sign of the sensible heat response compared to these other studies is not as expected, as mentioned in the discussion. A more thorough investigation of these results have been conducted and added to the results section and is further discussed and compared to the suggested references. As suggested by the referee, an analysis of the precipitation pattern to explain heat flux partitioning has been included in the revised manuscript.

III. See technical comments 15, 18 and 21 for further details on changes in the manuscript.

Comment 3

I. “*More emphasis should be put on spatially different seasonal changes, which can be of opposite sign between winter and summer, due to different influences from solar radiation and evapotranspiration. Maybe show maps of latent and sensible heat flux changes for all four seasons or at least the winter and summer seasons (see also technical comments 2, 15, and 17).”*

II. The manuscript is rewritten to put more emphasis on seasonal changes by expanding section 3.2 about the seasonal anomalies, and including a statistical analysis on the monthly means. Also, the discussion is revised and expanded according to the seasonal focus.

III. For more specific references to manuscript alterations, see answers to technical comments number 2, 15 and 17.

Technical comments:

Comment 1

I. “*Abstract: Line (L.) 2: “Arctic” not “arctic””*

II. Corrected

Comment 2

I. “*Abstract: L. 14: Is the increase in latent rather than sensible heat fluxes occurring in all seasons? Please clarify. See also Snyder and Liess (2014) and Jeong et al. (2011,2014) about their seasonal results and compare your results to these papers in the discussion.”*

II. The significant changes to the heat fluxes occur only during the summer months (see above answer on comment 2 related to the significant changes).

III. The following has been changed in the abstract; “We find that a northward migration of evergreen needle leaf forest into tundra regions causes an increase in latent rather than sensible heat fluxes during the summer season. Shrub expansion in tundra areas has only small effects on surface fluxes. Perturbations simulating the northward migration of mixed forest across the present southern border of the boreal forest, has largely opposite effects on the summer latent heat flux, and acts to moderate the overall mean regional effects of structural vegetation changes on the near surface atmosphere. “

Added to discussion; “These findings are supported by modeled findings for heat flux changes resulting from similar vegetation changes (Snyder and Liess, 2014 and Jeong et al. 2011,2014). Snyder and Liess (2014) found annual mean increases in both sensible and latent heat fluxes as response to lowered albedo and increased net radiative forcing. For the summer months, the increased radiative flux was partitioned into sensible rather than latent heat, due to re-partitioning of evaporative flux, leading to a JJA temperature increase of 0.4 K, and little or no increase in near surface humidity and precipitation. Jeong et al. (2014) on the other hand, found increases in both latent and sensible summer season fluxes in response to arctic greening, leading to relatively large increases in JJA near surface temperatures (1.95 K).”

Comment 3

I. “*Page (P.) 15509, L. 18: Delete "and"”*

II. Corrected

Comment 4

I. ” P. 15509, L. 26: Are there any references for successful simulations with dynamic vegetation models? Some studies such as Jeong et al. (2011,2014) had difficulties representing the observed changes in vegetation, but could still be cited here.”

II. We greatly appreciate the referee's suggestions for additional references, and have added the suggested citations to the introduction.

III. *P. 15509, L. 26:* the suggested citations are added.

P. 15510, L. 5:"Bhatt et al. (2010), link increased high latitude ecosystem productivity to a decrease in near-coastal sea ice and summer tundra surface temperatures, supporting the findings of Jeong et al. (2014), who concludes that vegetation-atmosphere-sea ice interaction gives rise to additional positive feedback of the Arctic amplification based on a series of coupled vegetation-climate model simulations under 2xCO_2 environment."

Comment 5

I. "*P. 15511, L. 13: Discuss the influence of vegetation on ground heat flux, or cite previous work such as Yang et al. (1999, JGR 104, D16, 19505–19514).*"

II. Suggested reference added.

III. P. 15511, L. 13: Reference added.

Comment 6

I. "*P. 15512, L. 18: Mention either here or in the discussion that these model setups are not able to measure downstream effects originating from outside the WRF domain, since meteorological forcing is only modified locally.*"

II. This is a good point, and specification is added to the methods section.

III. P. 15513, L. 28 : "As the meteorological conditions are only altered as response to the vegetation shifts inside the modelled domain, the simulation setup is not able to estimate downstream effects of vegetation perturbations."

Comment 7

I. *P. 15513, L. 10: Typo: "choice"*

II. -corrected

Comment 8

I. "*P. 15514, L. 1: The MODIS IGBP data used in WRF include the annual cycle. The word "static" might be misleading. This should be clarified.*"

II. The expression is changed to avoid confusion.

III. P. 15514, L. 1: “static land data” is changed to “land use data”

Comment 9

I. “*P. 15515, L. 1: "shift" should be singular here.”*

II. -corrected

Comment 10

I. “*P. 15516, L. 25: Be more specific about the difference between Ex 2 and Ex 1, and state something like "in addition to the changes made for Ex 1, the second experiment... also...". Currently, it is not clear if all Ex 1 modifications are also exactly included in Ex 2, or if only the general structure is maintained.”*

II. Corrected by adding the suggested sentence in line 27

III. P. 15516, L. 27: Added: “in addition to the changes made for Ex 1, also”

Comment 11

I. “*P. 15518, L. 16: Again, are these results statistically significant? The authors should perform some sort of statistical test to show the relevance of the detected changes.”*

II. As described above, a statistical analysis is performed on the 10 year averages, and on a seasonal level, indicating that the changes in mean monthly sensible- and latent heat fluxes are significantly different from control simulation during the summer season for both the areas of evergreen forest expansion into tundra vegetation, and in the areas with mixed forest expansion. The 10 year mean response is largely dominated by the summer season results, and this is clarified in the revised manuscript. The statistical analysis is performed on a seasonal scale and is therefore added in Section 3.2. The results for the monthly mean boundary layer height does not prove statistically significant, and the description of this variable is therefore omitted in the results section and corresponding Figure 5 is removed. The results for the 2 meter temperature show surprisingly small response to the vegetation perturbations, too small to yield statistically significant changes on a monthly mean scale. However, we regard this as an important feature of the results, and it is accordingly commented on in the revised manuscript.

III. P. 15518, L. 23: Added; “There are large seasonal variations in the sensible heat response, and these results are largely reflecting the summer season results (see sect. 3.2).”

P. 15519, L. 10: Added; “A statistical analysis of the surface fluxes is presented in sect. 3.2.”

P. 15520, L. 4: Added; “The weak response in the 2 m temperature is a result of the offset of lowered surface albedo by the increase in latent heat flux, yielding insignificant differences in the 2 m temperature for all seasons (Sect.3.2).”

P. 15520, L. 12: Added; “Seasonal statistical significance of corresponding variables is presented in Sect 3.2. “

Furthermore, figures 4,5,6,9 and10 are updated according to the statistical analyses.

Comment 12

I. “*P. 15520, L. 7: How can this cooling be explained? Please discuss the above results for sensible heat flux here.”*

II. Explanation for the observed cooling is added, along with specification of the significance of the result. Further discussion of the result is added in the discussion section.

III. *P. 15520, L. 7:* Added; “This cooling can be explained by the increase in surface albedo related to this vegetation perturbation, yielding less warming of the surface/canopy and corresponding weaker heat transfer by turbulent heat fluxes to the atmosphere.”

P. 15520, L. 12: “Seasonal statistical significance of corresponding variables is presented in Sect 3.2. “

Comment 13

I. “*P. 15520, L. 18: Fig. 8 only shows wind differences. We don’t know if there are decreased northward winds or increased southward winds. Please either show the wind field in the control experiment or rephrase to something like "reduced northward component". In general, wind fields can be represented by vectors with a reference vector in the legend to save space. However, for the present analysis it might be sufficient to show the change in absolute wind speed (sqrt(uˆ2+vˆ2)) in a single figure and relate the results to the heat fluxes.”*

II. This is a good point, and the figure is changed as suggested. The absolute wind speed is presented, and relevance to the presented heat fluxes is explained in the revised manuscript.

III. Figure 8 is replaced.

P. 15520, L. 16 :“The changing wind speed is closely related to the perturbations to the surface roughness length, and influences the turbulent heat fluxes. The reduced wind speed in the northern part of the domain contributes to decreases in the heat fluxes, and an opposite effect can be expected along the area of mixed forest perturbation.”

Comment 14

I. “*P. 15521, L. 2: Can the authors mention if there is a change in the annual cycle of soil moisture due to the change from evergreen to deciduous forests?”*

II. The soil moisture somewhat decreases in March and April and increases in July through October in response to the change from evergreen to deciduous forest. However, the monthly mean differences are only statistically significant in the area of evergreen forest expansion into tundra regions for spring and summer for the upper layer, and all year round for the bottom layer.

III. *P. 15521, L. 2:* Added; “The other vegetation changes do not significantly affect the soil moisture content, however the change of evergreen trees into mixed deciduous forest influences the annual cycle of soil moisture content by decreasing it in spring and increasing it in late summer and fall“

Figure 10 is altered and the seasonal impact on soil moisture is added, along with indications of statistical significance.

Comment 15

I. *P. 15521, L. 22: On p. 15511 l. 8-10, the authors write "Eugster et al. (2000) found that in general evergreen conifer forests have a canopy conductance half of that of deciduous forests, resulting in a higher sensible heat flux" and also Snyder and Liess (2014) and Jeong et al. (2011,2014) found an increase of sensible heat flux after evergreen forest expansion due to reduced albedo during summer. How can sensible heat flux be reduced here? Or, how is sensible heat flux defined in this study? Maybe an analysis of precipitation can shed some light on this discrepancy?*

II. Our findings are in line with Eugster et al., (2000), with reduced sensible heat flux going from evergreen forest to deciduous (mixed) forest along the southern border of our domain. However, as the referee points out, they do not match the findings of Snyder and Liess (2014) and Jeong et al. (2011,2014) with regard to changing vegetation category from tundra to evergreen forest. The referee suggests an analysis of the summer precipitation, which has been conducted, and added to the discussion of these results in the discussion section.

III. P. 15527, L.17: "The results show an increase in summer precipitation in areas with northward migrating evergreen forest, compared to the control simulation. An analysis of the mean JJA rainfall in this area alone shows an increase in accumulated rainfall of 3,35% over the ten summers. Increased rainfall would increase the partitioning of increased absorbed radiation (due to lowered albedo) into latent rather than sensible heat flux.

Comment 16

I. "*P. 15522, L. 1: How can 2 m temperature increase with "a reduction in heat transfer to the atmosphere"? Please clarify if sensible or latent heat flux is meant, or both.*

II. Only sensible heat is meant, and manuscript is adjusted accordingly.

III. Corrected to "sensible heat flux".

Comment 17

I. *P. 15522, L. 24: Spring and summer are considered the seasons with strongest PBL eight increase in Snyder and Liess (2014) due to strongest sensible heat flux increases. why is summer opposite of spring in Ex 1 in this study? Again, the authors should check if the model produces excessive summer rainfall in Ex 1, which might also explain the increase in latent heat flux and 2m moisture."*

II. After conducting a statistical analysis of these results, the PBL height differences are not statistically significant, and will be omitted in the results section, and only mentioned in relation to the sensible heat flux in the discussion section. As mentioned in comment number 15, further discussion of the heat fluxes with relation to summer precipitation is added to the discussion section, as suggested by the referee.

III. P. 15522, L. 18-28: Analysis of the PBL height is removed from the results section.

Comment 18

I. *P. 15523, L. 6: This cooling is opposite of previous findings by Liess et al. (2012), Snyder and Liess (2014), and Jeong et al. (2011, 2014) possible reasons should be discussed (sensible heat etc.)*
II. The description of the seasonal variations in the 2 m temperature is revised, and explained in relation to the sensible heat fluxes and the statistical analysis.
III. P. 15522, L. 1-12: Revised; “The effects of vegetation changes on the 2 m temperature are complex and vary across the areas of vegetation shifts and seasons (Fig. 10, lower right panel). However, despite in part large effects on surface heat fluxes, the overall 2 m temperature response is low and the monthly mean not statistically significant. In areas with shrub expansion there is a small, yet persistent year-round positive effects on the temperature compared to the control run, with the largest effects occurring in fall and winter months. In areas with evergreen forest expansion we see a wintertime heating, whereas the summer time effect is opposite, causing a cooling of the 2 m temperature in June through August, reflecting the decrease in sensible heat flux in the same period. The effect of the mixed forest migration is a modest year-round cooling of the 2 m temperature, and the effect is largest in the spring and autumn months, and lowest in mid-summer. The overall effect is a net increase in 2 m temperatures in winter, and decreasing 2 m temperatures in summer (solid line). This is accounting for all vegetation shifts. “

Comment 19

I. *P. 15524, L. 8: What does "energy limited rather than water limited" mean? Evaporation is related to temperature and kinetic energy from the low-level wind field.*
II. The term energy limited refers to areas in which the actual evaporation is limited by the radiative energy available, rather than the water available in the soil and canopies, which is the case in water limited regimes. Explanation is added to the revised manuscript for clarity.
III. P. 15524, L. 8: Changed into “This indicates that the soil moisture content does not limit the rate of latent heat, suggesting that the latent heat flux is limited by the available radiative energy, rather than available water (Seneviratne et al., 2010).”

Comment 20

I. *P. 15524, L. 13: Can the authors comment on the rooting depth for forest vs. shrubs here? If forests have higher rooting depth, they are less affected by lower soil moisture in the upper layers.*

II. This is a good point, as the rooting depth of the evergreen forest is four root layers, instead of three, as is the case with the shrub/tundra.

III. P. 15524, L. 13: Added; "Also, the evergreen forest can reach four root layers rather than three, which is the case for the tundra, making more soil water available to the evergreen forest."

Comment 21

I. *P. 15527, L. 2: These results by Beringer et al. (2005) are consistent with the WRF experiments by Liess et al. (2012), but Fig. 4 in the present study shows decreases. Again, the present results might show different sensible heat flux based on possible precipitation increase. Please check this and discuss a possibly different WRF setup used here.*

II. As the referee correctly suggests, the vegetation shift does lead to an increase in the summer precipitation, which acts to increase the evaporation and thereby the latent heat flux rather than the sensible heat flux in the area. With regard to the model setup, rain is produced in both the microphysics scheme and in the cumulus scheme. There are several options for such schemes within the WRF framework, and results could well be influenced by the choices made for these, along with the choices related to the applied vegetation changes. Further discussion on this subject is added to the discussion.

III. P. 15527, L. 17: Added ; "Also, the applied vegetation perturbations lead to increases in summer precipitation in the region, acting to increase the latent rather than the sensible heat flux. Our results show an increase in summer precipitation in areas with northward migrating evergreen forest, compared to the control simulation. An analysis of the mean JJA rainfall in this area alone shows an increase in accumulated rainfall of 3,35% over the ten summers. Increased rainfall would increase the partitioning of increased absorbed radiation (due to lowered albedo) into latent rather than sensible heat flux. Also, the specifics of vegetation perturbations made might influence these results. Here, we have chosen to only perturb the vegetation type in each area. The greenness fraction is not altered, which might influence the results with regard to the evapotranspiration and thereby available energy for sensible heat, as demonstrated by

(Hong et al., 2009). Further investigation of the sensitivity of these parameters is beyond the scope of this study, but certainly important subjects for further work."

Comment 22

I. *P. 15529, L. 20: See comment 19.*

II. See answer and corresponding manuscript changes in comment 19. The manuscript at this point is left as is, as the expression is explained earlier along with added citation.

References

Bhatt, U. S., Walker, D. A., Raynolds, M. K., Comiso, J. C., Epstein, H. E., Jia, G., Gens, R., Pinzon, J. E., Tucker, C. J., Tweedie, C. E., and Webber, P. J.: Circumpolar Arctic Tundra Vegetation Change Is Linked to Sea Ice Decline, Earth Interact, 14, 8, 2010.

Hong, S. B., Lakshmi, V., Small, E. E., Chen, F., Tewari, M., and Manning, K. W.: Effects of vegetation and soil moisture on the simulated land surface processes from the coupled WRF/Noah model, Journal of Geophysical Research-Atmospheres, 114, Artn D18118

Doi 10.1029/2008jd011249, 2009.

Jeong, J. H., Kug, J. S., Linderholm, H. W., Chen, D. L., Kim, B. M., and Jun, S. Y.: Intensified Arctic warming under greenhouse warming by vegetation-atmosphere-sea ice interaction, Environ Res Lett, 9, Artn 094007

Doi 10.1088/1748-9326/9/9/094007, 2014.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., and Teuling, A. J.: Investigating soil moisture-climate interactions in a changing climate: A review, Earth-Sci Rev, 99, 125-161, DOI 10.1016/j.earscirev.2010.02.004, 2010.

Final author response to anonymous referee #2

Bg-2014-478: "Long term effects on regional European boreal climate due to structural vegetation changes" by J. H. Rydsaa, F. Stordal, and L. M. Tallaksen

The referee comments are answered in the following way:

I. the referee comment in italics
II. author response comments
III. reference to corresponding changes in the manuscript.

General comments:

Comment 1

Due to the length of the comment, we have taken the liberty to divide it into smaller sections and for clarity answer each section separately.

I. "*The manuscript aims to use the state-of-the-art Weather Research and Forecasting numerical meteorological model investigate the impact on regional scale surface variables and mesoscale circulation due to land cover change alone. The experiment is conducted over a sufficiently long enough period to capture considerable inter-annual variation in meteorological drivers. The subject matter is interesting and relevant to a range of researchers, and correctly identified that mesoscale effects have not to date been full addressed, comparatively to global scale or local experiments. Despite the relevance of the work conducted here I have concerns regarding the model setup used. There are a number of details which need to be explained first".*
II. We greatly appreciate the referee taking the time to read and comment on our manuscript, and the positive response regarding the subject of this study. Regarding the model setup used, we have aimed to use the model in a way that is specific enough to meet the requirements of the study, yet general enough for results to be of interest for other users in the community. Also, considerations have had to be made with regard to the cost of the simulations required. However, we realize that a number of these considerations have not been properly addressed in the manuscript, and expand the manuscript accordingly.

I. “*The authors choose to use the default Noah land surface model (LSM) as opposed to the more advanced Noah-MP or Simple SIB models which are also available (and noted in the discussion). The Noah model has a number of, in my view, important disadvantages for this study. The most critical is that LAI in Noah is determine through an interpolation between min and max LAI parameters based on a greenness index provided to WRF as inputs from its geogrid files and it therefore insensitive to changes in meteorological drivers which would impact LAI through changes in terrestrial carbon cycle. Moreover I’m unsure how realistic it would be to use new PFT applied to the existing vegetation greenness?*”

II. We acknowledge that the Noah LSM is not the most advanced LSM available and does have weaknesses in its representation of the land surface. This could yield less realistic results for land-atmosphere interactions than more advanced models. The LAI in the NOAH land surface model is as the referee points out, insensitive to meteorological factors, which does lead to less detailed modeling of land surface behavior. However, as the aim of our study is to test effects of changes in certain surface properties related to simplified vegetation perturbations as isolated as possible, it is our opinion that this much used and tested LSM does represent the land surface well enough for the purpose of this study. We do however admit that we may not have justified the choice of model thoroughly enough in our manuscript and will give a more thorough explanation for our choice. The choice of model had to balance between satisfyingly representing important surface properties, while also yielding easily interpretable results and one way responses.

I. *“I also wonder how appropriate it is to use a model which is insensitive to the feedbacks it may drive in mesoscale circulation (i.e. no carbon cycle is included). An alternative would be to use Noah-MP which includes a carbon cycle and has the option of allowing the LSM to dynamically respond to meteorology. The authors could also then considered the magnitude of these feedbacks by running both with dynamic LAI switched on and off.”*

II. The inclusion of a carbon cycle in these experiments would certainly be interesting, and will be considered for future work. However, in this study, the feedback loops would give results that would be more complex and add complexity that we wanted to avoid in this study. It would also, as the referee points out in the next comment, yield a setup more sensitive to representation of the atmosphere, and require forcing representative of some future climate scenario. As a first step, it was in our opinion more informative to run a model with a more simple response vegetation perturbations, and as a next step, we increase complexity and include more dynamical factors. As a follow-up study to this, we would like to increase spatial and temporal resolution, and aim at more specific response mechanisms and if possible also include a more complex surface parameterization, possibly with different climate forcing.

I. "*Regardless I have number of issues with the approach taken, if the objective is to know the response of the land surface in isolation then this is difficult. Under current climate we don't expect to find these ecosystem so far north therefore their impact will be difficult to interpret as the response of the simulated land surface here will not respond to climate as the real forest would, due to the lack of a C-cycle. Similarly the response of an LSM with a C-cyle may not be informative as to the response under dlimate change as the vegetation is being exposed to current and may respond differently. I see this as a difficult question to address in comparison to say land cover change experiments when both PFTs already exist within the same climate envelope (e.g. afforestation experiments).*"

II. We appreciate that the referee acknowledges our dilemma when it comes to balancing accuracy with respect to vegetation and climate response, versus simplicity in experimental setup. Modeling a realistic atmospheric response to theoretical future vegetation perturbations does represent several uncertainties, as the referee points out. There are many ways of handling this, e.g. by either increasing model complexity to take into account as many influencing factors as possible (i.e. dynamical vegetation, climate scenarios, chemistry and dust/fire modeling), or by reducing complexity and dividing response mechanisms into smaller, more isolated effects which can then be better understood, such as the aim is in this study. Although the climatic response as such is not complete, it is our opinion that such simplified experiments may still contribute to increase understanding of likely atmospheric response mechanisms to future vegetation changes, when interpreted with caution.

I. "*If the intention is to consider structural impacts explicitly then a more logical approach (to me at least) would be to frame the research question as an impact /*

sensitivity analysis of changing parameters / characteristics. If this is the case then I think that the simulations conducted are sufficient but need to be discussed in the context of the structural changes rather than forest expansion specifically you have not simulated a forest that can respond dynamically to meteorology."

II. This is our intention precisely, and we understand that we have not been able to communicate this intention well enough in the manuscript. We realize that our linking of the changing parameters to certain vegetation migration patterns may have given the impression that we felt these changes were sufficient to represent a full dynamical forest migration. However this is not the case. Our intention is to provoke an atmospheric response to certain physical surface changes related to specific vegetation changes in the boreal domain. This is done through theoretical perturbations of vegetation patterns, and is as such, as the referee points out, a sensitivity study and will be framed more clearly as this.

III. P. 15507, line 1: The title is changed in accordance with the manuscript changes: Altered:" Sensitivity of regional European boreal climate to changes in surface properties resulting from structural vegetation perturbations."

P. 15512, line 11-19: Rewritten; "This study is a sensitivity study in which we investigate the effects of altered land cover properties on fine resolution surface fluxes and regional scale atmospheric response mechanisms by conducting two experiments with manually altered vegetation distribution. These experiments represent two potential future boreal and arctic ecosystem changes, and are compared to a control present day state of vegetation distribution. An invariant vegetation distribution in each simulation aims to isolate effects of changes in land surface properties related to structural vegetation changes on the regional climate. Meteorological forcing data in both simulations matches that of the control run to further isolate the long term effects of vegetation changes on the overlying atmosphere."

The abstract and the rest of the manuscript is further adjusted throughout to more precisely communicate the focus of the manuscript and reframe the research question more clearly towards a sensitivity study.

I. "*If the impact of the PFTs themselves is the targeted objective then offline runs of the LSM may be useful to show the coupled and uncoupled impacts or running WRF with boundary conditions provided by one or more climate change scenarios. I'm quite willing to accept that I may have misunderstood the authors objectives and methods.*

Much of my above comment may be irrelevant depending on what further details can be provided as the model arrangement. I think there is a lot of detail on how the land surface is parameterised and driven which is not specified (i.e. how LAI is derived in this experiment).”

II. We realize that our objective should be clarified and framed somewhat differently as mentioned in the previous point. Also, more details of the model parameterization and forcing will be provided as part of the methods section.

III. See previous general comment and specific comment number 11 for adjustments in the manuscript.

Specific comments:

Comment 1

I. “*The introduction contains insufficient review of previous works which looked at land cover change and their impact of surface meteorology. I realize that many of these studies have a focus on the terrestrial carbon cycle and land use change but many also consider impacts on surface meteorology e.g. Betts et al., 2007, Arora and Montenegro 2011. The introduction also suffers from some awkward sentences”.*

II. The introduction will be revised and the suggested references are added. In addition, other citations to studies related to atmospheric response to vegetation changes are included in the revised introduction.

III. Page 15512, line 10: “Snyder and Liess (2014) applied a one grid cell northward shift in boreal vegetation in a global climate model, to explore the response of the overlying atmosphere to a vegetation shift expected to occur within a century. Results of this shift show an annual warming of 0.3 ◦C mainly due to decreased surface albedo.”

Page 15512, line 15: “For instance, by investigating the climate benefits of afforestation mitigation strategies, Arora and Montenegro (2011) found that in high latitudes, the warming effect of decreased surface albedo related to increased forest cover, dominated the cooling effect of increased carbon sequestration, supporting similar findings of Betts et al. (2007).”

P. 15509, L. 26: Jeong et al., (2011,2014) citations are added.

P. 15510, L. 5: Revised; “Bhatt et al. (2010), link increased high latitude ecosystem productivity to a decrease in near-coastal sea ice and summer tundra surface temperatures, supporting the findings of Jeong et al. (2014), who concludes that vegetation-atmosphere-sea ice interaction gives rise to additional positive feedback of the Arctic amplification based on a series of coupled vegetation-climate model simulations under 2xCO2 environment."

See below comments number 3 and 4 for revision of awkward sentences.

Comment 2

I. *"Page 15508, line 8: The WRF model number is given but this should be included in the methods as well."*

II. This is a good point, and the model number is added.

III. P. 15512, line 21: Added;" WRF V 3.5.1"

Comment 3

I. "*Page 15511, lines 14 – 17. This is poorly written, in the context of the statement the author, I assume, means that complex canopy structures led to a reduction in albedo and an increase in net radiation (?), rather than "...greater affected radiation erms...". As for being closely linked to sensible heat, they are coupled but so is latent heat being that both are driven by net radiation."*

II. As the referee points out, the sentence is unclear and is rewritten.

III. Page 15511, lines 14 – 17: Rewritten: "Thompson et al. (2004) found that increasing canopy complexity greatly affect the surface radiation fluxes, and is closely linked to both the latent- and the sensible heat flux. They conclude that the heating associated with more complex canopies may influence regional feedback processes by increasing boundary layer height through increased sensible heat flux."

Comment 4

I. "*Page 15511, lines 21-24. Nothing wrong with the statement but it is incomplete as both sensible and latent heat fluxes are turbulent fluxes and as the author correctly states the partitioning between sensible and latent heat will have an impact on boundary layer processes (although I realize how significantly the impact is poorly defined). But why is the impact on 'the overlaying atmosphere' instead of higher LAI impacting soil moisture?"*

II. We acknowledge that the sentence was confusing, and have rewritten it for clarity.

III. Page 15511, lines 21-24.: "They also argue that shifting the vegetation type towards one with higher leaf area index, may cause a shift in the dependence of the latent heat flux on the state of the overlying atmosphere and mesoscale weather systems, through the link between transpiration and the vapor pressure deficit in the surrounding air. As the correlation between latent heat flux and soil moisture was found to be low at all sites, shifting vegetation type was found to have less impact on the dependence on soil water content. "

Comment 5

I. *"Page 15512-15513, Description of WRF and Noah models, as alluded to in the general comments sections should be extended"*
II. As suggested, the model description is extended, with special emphasis on the land surface model.
III. Page 15512: changed/added; "WRF has been run with the Noah land surface model (Tewari et al., 2004), which is a well tested model widely used in the modelling community. In Noah, the ground surface consists of four soil layers, that are 10, 30, 60 and 100 cm thick respectively, adding up to a total soil depth of 2 m. The top layer is a combined vegetation, snow and soil layer, and surface properties are dependent on soil- and vegetation category. Each vegetation category is assigned range values for parameters related to the vegetation influence on land atmosphere interaction, such as the albedo, roughness length, stomatal resistance and leaf area index (LAI). The vegetation properties are further dependent on the greenness vegetation fraction, describing the vegetation density in each grid cell. The LSM controls the surface and soil water budget and computes surface water- and energy fluxes from the surface to the atmosphere. The turbulent fluxes are dependent on vegetation properties such as the stomatal resistance and LAI, and the surface roughness length in addition to the wind speed."

Comment 6

I. *Page 15513, lines 5-13. This information is probably better placed in a table.*
II. The suggested information is moved to Table 1.
III. Table 1 added to the revised manuscript.

Comment 7

I. *Page 15514, lines 5-16. Would be good if you provided area or proportional cover estimates to place the cover changes in context.*
II. This is a good point, the manuscript is changed as suggested.

III. Page 15514, line 16: Added; “This adjustment affects in total 12 grid cells representing 8748 km^2.”

Comment 8

I. *Page 15515, lines 9-10. How short of time span?*

II. It is our understanding that many such models update the vegetation cover as an immediate response to prescribed meteorological thresholds, or at some set frequency during the simulation (i.e. once a year), forcing the vegetation to follow their climate envelope with no delay time to migrate into new areas all through the length of the simulation period. This approach serves the purpose of assigning potential vegetation as response to new climate, however is has been pointed out that it might yield too fast response compared to observed migration rates, which we would like to point out in the manuscript. In order to clarify, we added the following to the manuscript.

III. Page 15515 , line 11: Added; “Many of these models simulate vegetation response to climate change based on accumulated values such as growing degrees days and precipitation values, forcing the vegetation to keep within their respective climate envelopes. In cases of rapid climatic changes, the vegetation may therefore move unrealistically fast into new areas, often within the timespan of a century.”
The section is also moved to introduction in the revised manuscript.

Comment 9

I. *Page 15517, lines 11-26. Some of this could be placed in the methods or is a repetition of the introduction and is not results.*

II. The section is revised, and parts are moved and deleted in accordance with the referee’s suggestions.

III. Page 15517, lines 11-13: Moved to Methods section. “The only difference between the simulations is the described changes in vegetation distribution and resulting feedback effects of these, as simulations are in all other aspects identical.”
Page 15517, lines 14-17: Deleted, as it is repetition of introduction.

Comment 10

I. *"Page 15518, lines 10-15. How is the increase in LAI achieved? This comes back to exactly how was the model setup. Is this purely to do with the max/min LAI parameters or has the 'greenness' index been altered etc?"*

II. In our experiments only the vegetation type (the pft) has been altered, and as our aim is to investigate sensitivity to vegetation type-related parameters rather than vegetation density, the greenness fraction is left unaltered. This is to avoid speculations related to the fractional cover in the applied vegetation shifts. The response in LAI is therefore as the referee points out only a result of the scaling between the vegetation categories specific maximum and minimum values. This is specified in the revised manuscript, and reference to model parameter table added for clarity. Furthermore, possible impact of the chosen method is included in the discussion.

III. Page 15518, lines 3-5: Rewritten; "The applied vegetation changes lead to alterations in key surface parameters such as surface albedo and leaf area index (LAI), corresponding to their new minimum and maximum values assigned to each vegetation category in the model parameterization (see Table 1)"
See also technical comment 11 for manuscript alterations to the discussion.

Comment 11

I. *"Page 15525, lines 11-19. Again this relates to how was the model setup. Assuming that greenness index is used to provide the LAI estimates how have you dealt with differences in seasonality for the index? You will have applied evergreen PFTs to locations for which the index may have been deciduous."*

II. As the referee correctly assumes, the greenness fraction is used to scale the LAI between each vegetation category's respective minimum and maximum values in this study and as the referee points out, this is not well enough explained in the manuscript. We have revised the manuscript to include a more thorough explanation for the chosen setup (see previous comment). Finally, possible impacts of these choices are added in the discussion.

III. Page 15527, line 17: Added: "Also, the specifics of vegetation perturbations made might influence these results. Here, we have chosen to only perturb the vegetation type in each area. The greenness fraction is not altered, which might influence the evapotranspiration and thereby available energy for sensible heat, as demonstrated by Hong et al. (2009). However, we considered this approach sufficient, as the greenness fraction only acts to scale the LAI (and other vegetation parameters) values within the vegetation specific range (as indicated in the plotted results for the variable). Applying the new vegetation category to new areas would not imply a scaling of the LAI to values outside the respective categories assigned range. Further investigation of the sensitivity of these parameters is beyond the scope of this study, but certainly important subjects for further work."

Comment 12

I. *"Page 15526, line 16. So why did you not use Noah-MP?"*

II. As mentioned in the general comments, although we agree with the referee that there are several good options with respect to the model chosen, and there are of course advantages with using a more sophisticated LSM. Although it is beyond the scope of this study, we agree that using Noah-MP would be an interesting choice for a more specific and in-depth further investigation of several of the aspects of vegetation –atmosphere interactions touched upon in this study. However, we considered the Noah model sufficient in order to provide answers for the research questions in this study, and advantageous with respect to simulation cost and simplicity of model setup. A more clear explanation of the choice of model is added to the methods section.

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~~Long term effects on~~Sensitivity of regional European boreal climate to changes in surface properties resulting from ~~due to~~ structural vegetation ~~changes~~perturbations

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Abstract

Amplified warming at high latitudes over the past decades has led to changes in the boreal and A~~a~~rctic climate system, such as structural changes in high latitude ecosystems and soil moisture properties. These changes trigger land-atmosphere feedbacks, through altered energy partitioning in response to changes in albedo and surface water fluxes. Local scale changes in the arctic and boreal zone may propagate to affect large scale climatic features. In this study, MODIS land surface data are used with the Weather Research and Forecasting model (WRF V3.5.1) and Noah LSM, in a series of experiments to ~~simulate the influence~~investigate the sensitivity of the overlying atmosphere to perturbations to the ~~of~~ structural vegetation ~~changes over a~~in the Northern European boreal ecosystem. Emphasis is placed on surface energy partitioning and near surface atmospheric variables, and their response ~~in order to investigate~~to ~~changes in atmospheric response due to~~ observed and anticipated ~~structural vegetation~~land cover changes. We find that ~~pa~~erturbations simulating northward migration of evergreen needle leaf forest into tundra regions causes an increase in latent rather than sensible heat fluxes during the summer season~~, increased near surface temperatures and boundary layer height.~~. Shrub expansion in tundra areas has only small effects on surface fluxes. ~~However, it influences near surface wind speeds and boundary layer height.~~ Perturbations simulating the northward migration of mixed forest across the present southern border of the boreal forest, has largely opposite effects on the summer latent heat flux~~surface fluxes and the near surface atmosphere~~, i.e. leads to a decrease, and acts to moderate the overall mean regional effects of structural vegetation changes on the near surface atmosphere.

1 Introduction

Amplified warming at high latitudes over past decades has led to changes in the boreal and arctic climate system, such as structural changes in high latitude ecosystems (Serreze and Barry, 2011;Chapin et al., 2010). This polar amplification of global warming is in part due to a cascade of local feedback mechanisms that act to increase the initial greenhouse gas forcing (Serreze and Barry, 2011;Overpeck et al., 1997). Extensive evidence gathered over the past decades, has established that changes in high latitude ecosystems are part of these mechanisms, through redistribution of physical surface properties ~~of the surface~~ controlling processes that act to amplify or reduce initial warming (Bonan, 2008;Beringer et al., 2001;Sturm et al., 2001;Chapin et al., 2005). Important mechanisms include changes in surface energy and water flux partitioning, which could affect regional or continental scale evapotranspiration-precipitation feedbacks (Thompson et al., 2004;Beringer et al., 2005;Eugster et al., 2000), and surface albedo (e.g. Betts and Ball, 1997;Chapin et al., 2005;Serreze and Barry, 2011). Physical changes may have the largest direct impacts on the local scale. However, local scale feedbacks may propagate to regional and continental scales through cross-scale links, and possibly lead to critical transitions in the large scale climate (Rietkerk et al., 2011). Bonan (2008) suggests that the boreal forest might through its control on high latitude surface albedo, especially during winter, have the highest biophysical effect of all biomes on the mean global temperature. Also, by investigating the climate benefits of afforestation mitigation strategies, Arora and Montenegro (2011) found that in high latitudes, the warming effect of decreased surface albedo related to increased forest cover, dominated the cooling effect of increased carbon sequestration, supporting similar findings of Betts et al. (2007).

Several global vegetation modelling studies have predicted potential vegetation changes in response to future warming and elevated CO_2 concentrations (e.g. Alo and Wang, 2008;Strengers et al., 2010;Sitch et al., 2008;Lucht et al., 2006;Jeong et al., 2011;Jeong et al., 2014). Common features in these studies include migration of boreal forest towards higher ~~and~~ latitudes and altitudes, i.e. northward expansion of trees and shrubs into tundra ecosystems, and replacement of boreal forest by more temperate vegetation species along the southern edges of the boreal zone. Soja et al. (2007) concluded that substantial observational evidence across the circumpolar boreal region over the past several decades, indicates that the biosphere in the region has already responded to climate changes in accordance with modelled predictions, if not faster. They found upper and lower tree lines in mountainous regions across

Siberia to have altered in response to a warmer climate, as predicted by global dynamic vegetation models (e.g. ~~;~~Jeong et al., 2011;Jeong et al., 2014). Some of the observed changes to vegetation are increased biomass production in high latitude ecosystems as response to higher temperatures and longer growing season.

Several studies based on remote sensing have confirmed increased photosynthetic activity related to increased plant growth and increased growing seasons over the past decades (Myneni et al., 1997;Piao et al., 2011;Bhatt et al., 2010). Bhatt et al. (2010), link increased high latitude ecosystem productivity to a decrease in near-coastal sea ice and summer tundra surface temperatures, supporting the findings of Jeong et al. (2014), who concludes that vegetation-atmosphere-sea ice interaction gives rise to additional positive feedback of the Arctic amplification, based on a series of coupled vegetation-climate model simulations under $2xCO_2$ environment. In addition, the northward expansion of boreal and arctic vegetation into to previously tundra covered regions, also referred to as the arctic greening, is a widely observed feature across the arctic region. Chapin et al. (2005) calculated that 2.3% of the treeless area in Northern Alaska has been converted to forest from tundra over the past 50 years, corresponding to an area of 11,600 km^2. They highlight the importance of this redistribution in vegetation on surface albedo and temperatures. By analyzing a wide range of independent sets of measurement data, they found that the changes in terrestrial summer albedo enhances high latitude warming locally by as much as 3 Wm^{-2} per decade, comparable to long term regional effects of an atmospheric CO_2 doubling. Although the heating signal is mainly due to a prolonged snow free season, they expect that the expansion of shrubs and trees into the former tundra zones is likely to contribute to enhance summer warming in the future. Xu et al. (2013) found that a decrease of high latitude temperature seasonality equivalent to a climatic 4 degrees latitudinal shift equator-ward, has been observed in the Arctic region over the past 30 years. They estimate that a further diminishment in temperature seasonality equivalent to a full 20 latitudinal degrees southward shift, could occur within this century.

However, not all boreal and arctic sites respond to increased temperatures with an increased biomass production. A second type of response to warming is a reduction in photosynthetic activity, referred to as browning. Lloyd and Bunn (2007) observed that while most high latitude ecosystems have shown a positive trend in seasonal photosynthetic activity over the past few decades, some boreal ecosystems, mostly in the continental interior, showed significant downward trends in photosynthetic activity as response to increased temperatures, especially in the last two decades. They explain this as a result of temperature stress, or temperature-induced moisture stress, related to increased rates of evapotranspiration.

Changes in surface vegetation properties have a direct effect on the surface fluxes of latent and sensible heat. The ratio between the two, the Bowen ratio (sensible to latent heat flux), is an important climatic measure and highly sensitive to surface physical properties (Wilson et al., 2002;Baldocchi et al., 2000). For instance, based on an analysis of available data on surface energy balance of the arctic and boreal ecosystems, Eugster et al. (2000) found that in general evergreen conifer forests have a canopy conductance half of that of deciduous forests, resulting in a higher sensible heat flux, and lower latent heat flux over evergreen conifer forests. They estimate a reduction in Bowen ratio in areas where a warming-induced shift from conifer forest to deciduous forest should occur. Arctic ecosystems, like light taiga and tundra ecosystems, also have a higher ground heat flux due to less shade by canopies, compared to forested sites (Yang et al., 1999).~~sites. Thompson et al. (2004) found that increasing canopy complexity greatly affect radiation terms, and is closely linked to the sensible heat flux. They conclude that the heating associated with complex canopies may influence regional feedback processes by increasing boundary layer height.~~ Thompson et al. (2004) conclude that the heating associated with more complex canopies may influence regional feedback processes by increasing boundary layer height through increased sensible heat flux. These findings were supported by Beringer et al. (2005), who measured warmer and drier fluxes moving along the transition zone from arctic tundra to boreal forest. They found a relative increase in sensible heat flux resulting in an increase in Bowen ratio from 0.94 to 1.22 going from tundra to forested sites. They also argue that shifting the vegetation type towards one with higher leaf area index, may cause a shift in the relationship between latent heat flux and the state of the overlying atmosphere and mesoscale weather systems through the link between transpiration and the vapor pressure deficit in the surrounding air.~~,~~ Shifting vegetation type was found to have less impact on the dependence on soil water content due to the low correlation to latent heat flux at all sites. ~~rather than influence the link to soil water content.~~

Changing vegetation and surface properties will through its control on surface fluxes of heat and moisture influence the planetary boundary layer, and general circulations patterns (Beringer et al., 2001;Pielke and Vidale, 1995;Liess et al., 2011). Recently, Liess et al. (2011) modelled whether or not changing vegetation cover in the arctic zone could influence even mesoscale circulation patterns. They simulated the effects of a moderate northward forest replacement of shrub ecosystems along the southern tundra circumpolar border zone, on the summer time polar front. They estimated a regional broadening and strengthening of the polar jet stream of up to 3 m~~/~~s^{-1}, and concluded that the effects of the regional forest expansion could reach even the stratospheric circulation.

Uncertainties within vegetation-climate modelling are ~~–~~large, especially with regard to future species redistribution and climate feedback (e.g. Friedlingstein et al., 2013). Investigating the response of the overlying atmosphere to specific structural changes in vegetation, may yield valuable information that might reduce uncertainties with regard to climate response to the complex present and future changes in boreal ecosystems. Limiting the uncertainties related to modelled potential vegetation changes, Snyder and Liess (2014) instead applied a one grid cell northward shift in boreal vegetation in a global climate model, to explore the response of the overlying atmosphere to a vegetation shift expected to occur within a century. This shift gave an annual warming of 0.3 ^{o}C mainly due to decreased surface albedo.~~Betts et al. (2007)~~

Changes in ~~species distribution~~migration speed in response to climatic changes vary greatly across species types. As ecosystems consist of complex, co-dependent, compositions of wide ranges of species, the total ecosystem migration speed will be equally complex. However, cross-species observational studies confirm a general northward- and altitudinal shift in the boreal area, a trend matching climate change predictions (Parmesan and Yohe, 2003;Chen et al., 2011). On a global scale, Chen et al. (2011) derived a median cross species migrations rate of 16.9 km per decade, nearly doubling the estimate of Parmesan and Yohe (2003) who derived an average range shift of 6.1 km per decade in their meta-analyses based on some 1700 species across the globe. These average rates of migration estimates are often seen in contrast to those of dynamic vegetation models, which often assume strict relationships between species redistribution and altered climatic environment, yielding sometimes abrupt changes in species composition in large areas over short time spans. Many of these models simulate vegetation response to climate change based on accumulated values such as growing degrees days and accumulated precipitation values, forcing the vegetation to keep within their respective climate envelopes. In cases of rapid climatic changes, the vegetation may therefore move unrealistically fast into new areas, often within the timespan of a century~~, depending in the length og the simulation/ experiment~~. To assess two extreme scenarios, in which species follow their climatic environment completely, or do not move out of their current habitats at all in spite of changing climatic conditions, Mckenney et al. (2007) investigated potential migration scenarios of 130 North American tree species, based on

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future climate predictions. They found that on average, a northward distribution shift of between 330 km and 700 km depending on the species' ability to migrate at the same rate as their current climatic conditions, was likely to occur by the end of this century, along with large decreases in future -potential habitats.

In t~~In t~~his study, we investigate the sensitivity~~, we investigate the sensitivity to~~ of altered land cover properties on fine resolution surface fluxes and regional scale atmospheric response mechanisms by conducting two experiments with manually altered structural vegetation distribution. These experiments represent two potential future boreal and arctic ecosystem changes, and are compared to a control present day state of vegetation distribution. An invariant~~ time-indifferent~~ vegetation distribution in each simulation aims to isolate effects of ~~structural vegetation~~ changes in land surface properties related to structural vegetation changes on the regional climate. Meteorological forcing data in both simulations matches that of the control run to further isolate the long term effects of vegetation changes on the overlying atmosphere.

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2 Model and methodology

The Weather Research and Forecasting model (WRF V3.5.1) is a non-hydrostatic, mesoscale weather prediction system (Skamarock and Klemp, 2008). It is a model with a wide variety of applications, across scales ranging from large-eddy to global simulations. Simulation time scales vary between short-term case studies of a few hours or less, to regional climate studies spanning decades. In this study, ~~the model~~WRF has been run with the Noah land surface model (Tewari et al., 2004), which is a well tested model widely used in the modelling community. -In Noah, the ground surface consists of four soil layers, that are 10, 30, 60 and 100 cm thick respectively, adding up to a total soil depth of 2 m. The top layer is a combined vegetation, snow and soil layer, and surface properties are dependent on soil- and vegetation category. Each vegetation category is assigned range values for parameters related to the vegetation's influence on land atmosphere interaction, such as the albedo, roughness length,

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stomatal resistance and leaf area index (LAI). The vegetation properties are further dependent on the greenness vegetation fraction, describing the vegetation density in each grid cell. ~~,~~ The LSM~~model~~ controls the surface and soil water budget~~-~~ and computes surface water- and energy fluxes from~~between~~ the surface to~~and~~ the atmosphere. The turbulent fluxes are influenced by vegetation properties such as the stomatal resistance and LAI, and the surface rougness length in addition to the wind speed.~~,~~ ~~and controls the surface and soil water budget.~~ The model is run at a spatial resolution of 27 km, with 52 vertical layers. The time resolution is two minutes, and output is written every 3 hours. The model setup is further presented in Table 1.~~includes the Mellor-Yamada-Janjic planetary boundary layer parameterization (Janjić, 1994), Morrison two moment microphysics (Morrison et al., 2009), RRTMG short- and long wave radiation options (Iacono et al., 2008) and the Kain–Fritsch cumulus scheme (Kain, 2004).~~ The choic~~s~~e of model configuration is based in part on sensitivity testing of various schemes (not shown), and in part out of considerations of available output variables of different parameterizations. A review of literature with regard to choices best suited for a cold region intermediate resolution simulation, and a consideration of the NCAR cold climate medium resolution example setup (Skamarock et al., 2008), and the Polar WRF setup (Hines et al., 2011), also contributed to the current model configuration.

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For the initial- and boundary conditions, we use the ERA Interim 6 hourly reanalysis. Boundary conditions for the years 2000-2010 are used for the simulations, where the first year is regarded a spinup year and not included in the analyses. The same boundary conditions are applied in all three simulations to isolate the effect of structural vegetation changes on the overlying atmosphere and climate. The 10 year simulation length was chosen in order to achieve a good estimate of the mean responses of the overlying atmosphere to vegetation changes without inter annual variation influencing the results. Although even longer simulations might be advantageous, 10 years was chosen as a compromise between length and computational cost while keeping high temporal and spatial resolutions in the simulations. The time period chosen as meteorological forcing (2001-2010) is coherent with the selected set of vegetation data and acts as a suitable reference period for present day conditions. As the meteorological conditions are only altered as response to the vegetation shifts inside the modelled domain, the simulation setup is not able to estimate downstream effects of vegetation perturbations.

For~~ static~~ land use data, the MODIS IGBP modified 21 class land surface data is used. This dataset is available with the standard WRF package download. The dataset is based on the original 1 km resolution MODIS IGBP vegetation map (Friedl et al., 2010), but excludes permanent wetland and has three tundra classes and lakes added by the Land Team at EMC/NCEP. To represent high latitude and altitude ecosystems more accurately, the vegetation category of open shrub land has been replaced by various tundra vegetation classes north of 60 degrees latitude in the modified MODIS dataset. This replacement results in an artificial shift in vegetation that can be detected along this latitude across a mountain plateau in southern Norway. In this study, the remaining grid cells of shrub land south of 60 degrees and west of 15 degrees east, are adjusted into wooded tundra below-, and mixed tundra above the height of the local tree line, to achieve a vegetation distribution more consistent with local ecosystems in this area. This adjustment affects in total 12 grid cells representing 8748 km^2. In the rest of the domain the vegetation shift along the 60 degree latitude has no abrupt shifts or other negative implications for the purpose of this study. The study area, which covers the northern European boreal zone, is shown in Fig. 1, represented by evergreen needle leaf forest as this is the dominant vegetation type in this area.

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2.1 Experiments

The goal of the experimental setup is to investigate the sensitivity of the land-atmosphere interactions to changes in the vegetation distribution. Perturbations to the land cover aims to represent a northward migration of boreal ecosystems based on the aforementioned observed and anticipated features in vegetation migration patterns. Experiments are designed to induce atmospheric response and feedback mechanisms, while keeping perturbation complexity low enough to be able to identify the respective response mechanisms related to each of the applied vegetation shifts. The aim has been to induce moderate and realistic scale changes, representative of actual vegetation shifts on a century long timescale.

~~Changes in species distribution in response to climatic changes vary greatly across species types. As ecosystems consist of complex, co-dependent, compositions of wide ranges of species, the total ecosystem migration speed will be equally complex. However, cross-species observational studies confirm a general northward- and altitudinal shifts in the boreal area, a trend matching climate change predictions (Parmesan and Yohe, 2003;Chen et al., 2011). On a global scale, Chen et al. (2011) derived a median cross species migrations rate of 16.9 km per decade, nearly doubling the estimate of Parmesan and Yohe (2003) who derived an average range shift of 6.1 km per decade in their meta-analyses based on some 1700 species across the globe. These average rates of migration estimates are often seen in contrast to those~~

~~of dynamic vegetation models, which often assume strict relationships between species redistribution and altered climatic environment, yielding sometimes abrupt changes in species composition in large areas over short time spans. To assess two extreme scenarios, in which species follow their climatic environment completely, or do not move out of their current habitats at all in spite of changing climatic conditions, Mckenney et al. (2007) investigated potential migration scenarios of 130 North American tree species, based on future climate predictions. They found that on average, a northward distribution shift of between 330 km and 700 km depending on the species' ability to migrate at the same rate as their current climatic conditions, was likely to occur by the end of this century, along with large decreases in future potential habitats.~~

W~~In this study, w~~e isolate the effects of specific vegetation changes by applying simplified perturbations to the dominant vegetation categories as given by the selected set of land use data. The perturbations each represent a given trend of forest migration in this area. As such, the perturbations are not to be regarded as estimates of future state of vegetation distribution in the area under a specific climate scenario, rather adjustments based on observed and anticipated trends applied for the purpose of this sensitivity study. No assumptions are made with regard to changes in vegetation density after redistribution. ~~Here, a~~A 10-year simulation period is used, and averages over this period are regarded as a good indicator of ~~mean~~ climate response to the perturbations. Assuming vegetation changes induced by a changing climate, this experimental setup is not relevant for an unlimited time span; rather it reflects moderate changes in simulated vegetation shifts. Keeping in line with the meta-analyses of migrations speeds across species and assuming a time horizon on the scale of about a century, an upper limit of a moderate 100 km vegetation migration is applied to vegetation redistribution. Perturbations related to vegetation shifts only imply changes in the biophysical properties of the surface, while biochemical, atmospheric and hydrological properties are not perturbed. The only difference between the simulations is the described changes in vegetation distribution and resulting feedback effects of these, as simulations are in all other aspects identical. As the vegetation cover is not able to react to meteorological forcing during the simulations (non-dynamical vegetation), the effects of the structural vegetation perturbations are one-way in this study, therefore all changes in the meteorological conditions as compared to the control simulation may be assumed a result of vegetation perturbations alone. The applied changes in dominant vegetation category for each experiment, as compared to the control simulation, are illustrated in Fig. 2.

2.1.1 Experiment 1

The main emphasis in the first experiment (hereafter Ex 1), is the widely documented feature of arctic shrub expansion into tundra regions. This change involves increase in surface roughness and wintertime albedo, as documented by e.g. Chapin et al. (2005). This is also regarded the most rapid of the applied vegetation shifts, and as such occupies the largest area of applied changes. To represent this vegetation shift, a moderate change in tundra vegetation is applied by changing the areas covered by the vegetation category of “mixed tundra” into “wooded tundra”, thereby slightly increasing the roughness length, and reducing the wintertime albedo (Table 2). In addition, to account for another important trend in the northernmost latitudes of our domain, we have ~~allowed for~~ made a perturbation representing the northward migration of the boreal forest~~,~~ by applying ~~the migration of~~ the land use category of evergreen needle leaf forest in~~to~~ areas previously covered by wooded tundra. The shift is applied up to 108 km to represent a slow migration towards higher latitudes in areas that already are covered by vegetation. This northward ~~migration~~ shift of dense forest implies an increase in LAI and decrease in albedo, owing to the denser canopy of the evergreen forest (Table 2). For Ex 1 these two vegetation changes imply changes in a total area of 563 517 km^2 of shrub expansion/tundra conversion and a minor area of 181 521 km^2 of northward migrating evergreen forest (Fig. 2, left panel).

2.1.2 Experiment 2

In the second experiment (hereafter Ex 2), the northward migration of the southern edges of boreal forest is also taken into account by ~~allowing for~~ applying a perturbation representing a northward migration of the southern border of the evergreen forest and its replacement of more temperate species. To achieve this, in addition to the changes made for Ex 1, also the southern border of the evergreen needle leaf forest is ~~allowed to migrate~~shifted northward by up to 108 km (similar to the migration of evergreen forest on the northern border), being replaced by the category of mixed forest, representing a slow transition towards a more temperate forest type. For the physical properties of the surface, this implies a decrease in maximum and minimum LAI values and increase in maximum and minimum albedo (Table 2).

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~~).~~ These vegetation changes cover a total area of 392 202 km^2 of northward migrating mixed forest, and represents as such a substantial shift in vegetation, although consistent with the northern vegetation perturbations in Ex 1.

~~The only difference between the simulations is the described changes in vegetation distribution and resulting feedback effects of these, as simulations are in all other aspects identical.~~

3 Results

~~The only difference between the simulations is the described changes in vegetation distribution and resulting feedback effects of these, as simulations are in all other aspects identical.~~ R~~As such, r~~esults are largely presented as differences between experiment simulations as compared to the control run. ~~The effect of vegetation changes on the atmosphere varies greatly both spatially and temporally, and the various feedback mechanisms vary in relative importance across time and spatial scales.~~ To account for inter-seasonal and inter-annual variations, we start by examining the long term average effects across the full length of the 10 year simulation period (excluding the spinup-year), largely focusing on regional means. Time averages are all based on the three hour output frequency, and as such represents mean day and night values. In addition, average changes over selected areas of specified vegetation shifts are presented to highlight the effects of individual vegetation changes. The main emphasis is on alterations in surface fluxes and near-surface atmosphere; however a short investigation of effects on soil moisture content is also conducted. We ~~further~~ investigate the seasonal variations ~~in feedback mechanisms~~ in Sect. 3.2 and try to further isolate conditional effects with regard to water deficits in soil and air in Sect. 3.3.

3.1 10 year averages: What are the overall effects of vegetation changes?

The applied vegetation changes lead to alterations in key surface parameters such as surface albedo and leaf area index (LAI~~)~~), corresponding to their new minimum and maximum values assigned to each vegetation category in the model parameterization (~~see~~ Table 2~~1~~)~~.~~. The 10 year average change in albedo due to structural vegetation changes is shown in Fig. 3. Here the difference between Ex 2 and the control run is shown to account for all applied vegetation changes. The effect on albedo and LAI changes are~~is~~ not constant throughout the year (~~see~~

Sect. 3.2) and across the domain, and is a result of the scaling between vegetation dependent prescribed min. and max. values by the vegetation greenness fraction throughout the year. The annual average features represented here, show that in areas with a northward migrating evergreen needle leaf forest, vegetation changes largely leads to a decrease in surface albedo, whereas areas with simulated shrub expansion do not affect the 10 year average albedo notable. The southern border change from evergreen needle leaf- to mixed forest leads to an increase in surface albedo. A general increase in LAI is seen in areas with a northward expanding evergreen needle leaf forest, whereas a decrease is seen across the area of mixed forest migration (Fig. 3, right panel). The areas of shrub expansion do not influence the LAI. The changes in these surface properties together with the roughness length, are largely what induces the changes in the land-atmosphere interactions described below.

The 10 year average changes in sensible- and latent surface fluxes as compared to control simulation are presented in Fig. 4 for both experiments ~~(all numbers refer to averages in areas with vegetation changes only)~~. Only statistically significant results at the 95% confidence level based on Student's t-test statistics are presented. The overall average effect of vegetation changes is a decrease in sensible heat flux to the atmosphere (left panels). Shrub expansion has only a minor influence on the average sensible heat flux. As seen in the lower left panel, the most pronounced negative effect is a result of the northward advancement of mixed forest (Ex 2). The northernmost expansion of evergreen trees into tundra also reduces the sensible heat flux, but not to the same degree. There are large seasonal variations in the sensible heat response, and these results are largely reflecting the summer season results (see Sect. 3.2). The reduction in sensible heat flux over the entire 10 year period for Ex 1 compared to control run, is ~~for Ex 1~~ 0.7 W m^{-2} for areas averaged over both shrub expansion and northward migrating evergreen forest (all numbers refer to averages in areas with vegetation changes only). The corresponding number for Ex 2, considering all vegetation changes, is a reduction of 1.4 W m^{-2}, mostly a response to the mixed forest northward migration (Fig. 7).

A contrasting pattern is seen in the effect on the latent heat flux (Fig. 4, right panel). The northward migrating forest and shrub expansion in Ex 1 are both enhancing the latent heat flux, with areas experiencing a northward migrating evergreen needle leaf forest, dominating the results (upper panels). The 10 year average response in Ex 1 is an increase in the latent heat flux by 1.2 W m^{-2}. This number also includes areas with tundra shrub expansion~~change~~, and the mean change over areas with northward expanding evergreen forest only, is 4.4 W m^{-2}. In Ex 2, the mean effect of vegetation migration is a reduction of the latent heat flux by 0.4

W m^{-2}, mainly influenced by the negative effect of the mixed forest expansion, in which areas the average latent heat flux is reduced by 3.5 W m^{-2}. There are large seasonal variations in the response of the surface fluxes, as presented in Sect. 3.2.

The changing wind speed (Fig. 5) is closely related to the perturbations to the surface roughness length, and influences the turbulent heat fluxes. The reduced wind speed in the northern part of the domain contributes to decreases in the heat fluxes, and an opposite effect is seen along the area of mixed forest perturbation.

~~The surface fluxes of latent and sensible heat greatly influence the planetary boundary layer, and the influence of the vegetation changes on the planetary boundary layer height (PBLH) for both experiments as compared to the control run, are seen in Fig. 5. Contradictory to the heat fluxes, the areas with the largest changes in PBLH are those with shrub expansion, causing a mean increase in the PBLH in the northernmost areas of the domain. Changes in the physical surface properties include the roughness length and small changes in wintertime albedo, whereas there are no changes in LAI. The northward migrating evergreen needle leaf forest is also influencing the boundary layer height although to a lesser degree, causing a mean increase, whereas the southern border mixed forest expansion causes an average reduction in the boundary layer height of about 22 m. The boundary layer height changes are, as the fluxes, closely restricted to areas with vegetation changes.~~

Figure 6 shows the 10 year average effect of vegetation changes on near surface atmospheric variables. The 2 m temperature (left panels) is sensitive to surface fluxes of sensible and latent heat, and to the surface radiative budget. The overall effect on this variable is a good climatic indicator of the effects of vegetation changes on the atmosphere. In Ex 1 we see the largest effect in the north-eastern part of the domain (upper left panel). The areas with the highest increase in temperature are dominated by, although not restricted to, areas with a northward expanding evergreen needle leaf forest. Temperature increase is also seen along areas of shrub expansion, although with a weaker average response. The 10 year average increase in 2 m temperature in these areas (total area of changed vegetation in Ex 1) is ~~a moderate~~ 0.11 ^{o}C~~, however with large seasonal variations~~. ~~(Sect. 3.2) .~~

The weak response in the 2 m temperature is a result of the compensating effect of the lowered surface albedo by the increase in latent heat flux, yielding small differences in the 2 m temperature. Al~~l~~so, reduced wind speed and decreases in heat transfer to the near surface atmosphere by sensible heat flux ~~n~~lowers the near surface temperature response.

In Ex 2 (Fig. 6, lower left panel) the dominant feature is the contrasting cooling effect of the southern border mixed forest northward migration. The annual average effect of this vegetation change is a cooling of 0.19 ^{o}C, which together with the northern vegetation shifts results in a total average effect of combined vegetation shifts of 0.0 ^{o}C, averaged over all grid cells with vegetation changes. This cooling can be explained by the increase in surface albedo related to this vegetation perturbation, yielding less radiative warming of the surface and corresponding weaker heat transfer by turbulent heat fluxes to the atmosphere. Figure 7 summarizes changes in near surface atmospheric variables, given as average effects resulting from vegetation changes in Ex 1 (left bars), Ex 2- Ex 1 (middle bars) and all of the vegetation changes, applied in Ex 2 (right bars). Seasonal statistical significance of corresponding variables is presented in Sect 3.2.

10 year average changes in planetary boundary layer height (PBLH) and surface pressure resulting from vegetation changes is shown in Fig. 8. ~~, left panels, along with changes in annual average wind patterns (right panels).~~ The PBLH is increased in the areas with shrub expansion and northward shifts in evergreen needle leaf forest, and decreased in areas with mixed forest northward expansion, reflecting the results for the turbulent heat fluxes and temperature changes. A pattern of increased surface pressure along the northern coastline of the domain is clear, especially over regions of northward expanding evergreen forest.

~~Changes in wind components (Ex 2 compared to control run) are shown for the eastward wind (upper, right), the northward wind component (lower, right). A pattern of increased surface pressure along the northern coastline of the domain is clear, together with a mean decrease in both eastward and northward winds, especially over regions of northward expanding evergreen forest.~~

Figure 9 show the 10 year average percentage change in volumetric liquid soil water content for Ex 2 compared to control run, for each of the four simulated soil layers. As demonstrated by the figure, the vegetation change most influential on the water content is the area of northward expanding evergreen forest into previously tundra covered area in the north of the domain. The change is larger deeper down in the soil, reflecting the fact that the number of root layers for the evergreen forest increases to four, as compared to the tundra, which only influences the three upper layers. The lowering of soil water content is a result of the ability of the evergreen forest to extract more water from the ground compared to the tundra vegetation, and is reflected in the increase in the latent heat flux in this area. The other vegetation changes do not significantly affect the soil moisture content~~ to any great extent~~.

However, the change of evergreen trees into mixed deciduous forest influences the annual cycle of soil moisture content by decreasing it in spring and increasing it in late summer and fall (Figure 10)~~–~~.

3.2 Seasonal averages; when are various effects largest?

Seasonal variations in surface- and near surface variables as results of the various vegetation changes are presented in Fig. 10. Each stippled line shows 10 year monthly mean changes for one type of vegetation change as averages only over the grid cells with the corresponding vegetation shift. The overall mean effect of all vegetation changes, averaged over the total area of all vegetation shifts, is shown in the black line marked Ex 2-Ctrl. Black circles indicate monthly area means passing the 95% confidence interval based on Student's t-statistics. Confidence intervals are computed from the control simulation monthly means for each area with changed vegetation, and circeled points as such represent months where the average values for each area are significantly different from the control simulation area mean.

For the albedo (Fig. 10, upper left panel), the decrease due to the northward migrating mixed forest is most prominent in spring and autumn months, whereas the increase is less over the summer and smallest during winter. The contrasting negative effect on the albedo resulting from the evergreen needle leaf tree northward migration is largest in fall and the mean effect throughout the year is a lowering of the surface albedo. The maximum change in spring and autumn months, reflect the close dependence on the LAI, which varies throughout the year. The effect in the winter months is on average small because of snow covering the vegetation. The spatial variability across the domain is largest in spring and autumn months (not shown), and smallest in summer, reflecting the fact that LAI changes occur at an uneven rate across the domain in these transitional periods (the changes in albedo and LAI results from changing parameter values, and are therefore not satistically tested).

The largest effect on the sensible heat flux (Fig. 10, middle left panel), is seen in areas of evergreen needle leaf forest expansion in summer, on average reducing the heat flux by 11.2 W m^{-2} in July. In winter and autumn the effect on the sensible heat flux is reversed as result of this vegetation change, increasing the heat flux in these areas, especially in autumn. The shrub expansion only has a weak decreasing effect on the sensible heat flux in summer. The mixed forest migration has a pronounced year-round effect on the sensible heat flux, with the most prominent reduction in spring and early summer. The overall effect of all vegetation changes (solid line) is close to zero in winter, and a reduction in sensible heat flux~~transfer~~ to the atmosphere is seen over the summer.

For the latent heat flux (Fig. 10, middle right panel), the effect of the shrub expansion is ~~very small~~low, and the two types of forest expansion dominate the results in contrasting ways. The evergreen needle leaf forest expansion causes a sharp increase in summer time latent heat fluxes compared to the control run, with a peak in July of on average as much as 18 W m^{-2}. The mixed forest expansion on the other hand, acts to decrease latent heat fluxes all year round, and the decreasing effect is largest in June with an average reduction of about 10.3 W m^{-2}. The net effect is a year- round slight decrease in latent heat fluxes from the surface to the atmosphere, with largest effect in spring (solid line).

The 2 m humidity varies on a monthly basis similar to the latent heat flux, as these two variables are closely linked. The effect on humidity is dominated by the two types of forest migration, whereas the effect of shrub expansion is small. The evergreen needle leaf forest expansion has a prominent positive effect, increasing the humidity especially in summer, whereas the mixed forest expansion acts to decrease the 2 m humidity in these areas, having the largest effect over the summer months (not shown). The humidity is dependent on the soil moisture through transpiration and ground evaporation.

~~The overall combined effect of all vegetation changes on the height of planetary boundary layer (PBL) is lowest in summer and largest in spring (Fig. 10, lower left panel, solid line). The vegetation change most influential on the PBL is the shrub expansion during winter and spring, increasing the PBL all year round and by as much as 33.7 m on average in March. Also the northward expansion of evergreen needle leaf forest contributes to an increase in boundary layer height in the winter months; however in summer this vegetation change causes a sharp decrease as compared to the control run, possibly related to decreases in sensible heat flux and surface temperature. The northward expansion of mixed forest along the southern border of the boreal forest causes a year-round decrease in PBL height, with the smallest effect in summer months, and the most pronounced decrease in May.~~The soil moisture content is most prominently affected by the conversion of tundra to evergreen forest, as the forest subtracts more soil water from all four layers compared to the tundra vegetation. As a result of the increased rooting depth, the most prominent effect is on the bottom layer (layer four), as presented in Fig. 10 (lower left panel).

The effects of vegetation changes on the 2 m temperature are~~is~~ complex and vary~~ies~~ across the areas of vegetation shifts and seasons (Fig. 10, lower right panel). However, despite in part large effects on surface heat fluxes, the overall 2 m temperature response is low, and the area mean differences are not statistically significant. In areas with shrub expansion there is a small, yet persistent year-round positive effects on the temperature compared to the control run, with the largest effects occurring in fall and winter months. In areas with evergreen forest expansion we see a wintertime heating, whereas the summer time effect is opposite, causing a cooling of the 2 m temperature in June through August, reflecting the decrease in sensible heat flux in the same period.~~-~~ The effect of the mixed forest migration is a modest year-round cooling of the 2 m temperature, and the effect is largest in the spring and autumn months, and lowest in mid-summer. The overall effect is a net increase in 2 m temperatures in winter, and decreasing 2 m temperatures in summer (solid line). This is accounting for all vegetation shifts.

3.3 Conditional effects; under which conditions are effects largest?

The latent heat flux is mainly the combined effect of soil evaporation, transpiration and evaporation from interception. The part most closely linked to the specific type of vegetation cover is the evapotranspiration (i.e. transpiration and evaporation of intercepted water), which depends on water availability (either as intercepted water or to the plant through the roots), the efficiency of turbulent transfer and the evaporative power of the ambient atmosphere. As both the number of soil layers available to the plants roots, and the LAI and thereby the rate of evapotranspiration, varies across vegetation types, the dependence of latent heat (and thus the evapotranspiration) on soil moisture as compared to the vapor pressure deficit (VPD) in the surrounding air, may shift as vegetation category changes. To investigate these effects in more detail, the effects of selected vegetation changes on the relationship between the latent heat flux and soil moisture, and latent heat flux and ambient air vapor pressure deficit, are shown in Fig. 11. The effect of shrub expansion on surface heat fluxes is low, and so we focus here on areas with forest migration. As fluxes and flux response to vegetation shifts are largest in summer months, only monthly averages of the summer season (JJA) are used, and correlation coefficients based on averages in each area are given. Changes averaged over areas with evergreen forest expansion into tundra is shown in the upper panels, and mixed forest northward migration in the lower panels. The white circles indicate monthly mean values as simulated in the control run, and black dots represent monthly mean values averaged over the same area after vegetation shifts.

T~~For the evergreen forest expansion t~~he correlation coefficient between latent heat flux and soil moisture content is low, regardless of vegetation type. This indicates that the soil moisture content does not limit the rate of latent heat, suggesting that the latent heat flux is limited by the available radiative energy, ~~energy limited~~ rather than available water~~ limited~~ (Seneviratne et al., 2010). The latent heat's correlation to VPD is increased from 0.68 to 0.74 when changing vegetation from tundra to evergreen forest, indicating that the evergreen forest latent heat flux is more dependent on the ambient atmosphere than the tundra vegetation it replaces. Also, the evergreen forest can reach four root layers rather than three, which is the case for the tundra, making more soil water available. For the mixed forest northward expansion, the same shifts in correlation occurs, indicating that shifting vegetation type from evergreen forest to mixed forest also acts to increase the latent heat flux dependence on VPD rather than soil moisture.

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4 Discussion of results

Perturbations in this study were limited to changing the dominant land category in given areas, and accordingly to changes in certain physical properties of the surface. The parameterization of physical processes in the model has not been altered, in order to maintain a high relevance to other studies. The modified IGBP MODIS vegetation dataset is regarded a suitable basis for perturbations, although many alternatives do exist with regard to datasets, and vegetation perturbations that will influence the results. Liess et al. (2011) used the IGBP MODIS land cover dataset in which no alterations have been made to the land use category of “open shrub land” as is the case for the modified MODIS dataset (where replaced by various tundra vegetation classes). They found the open shrub land use class a suitable category for forest conversion across the arctic and northern boreal domain. This represents a similar, but somewhat larger land use change than the ones applied in our study, although in good agreement with observational data and estimates for future changes in the area (Liess et al., 2011). We have not made any assumtions related to the vegetation coverage after changing vegetation type, i.e. the greenness vegetation fraction is left unaltered.

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The perturbations applied here represent simplified estimates of future vegetation distribution, based on observed trends in vegetation migration in the area. As such, the results are not possible to validate against time- and site-specific observations. However, some general features resulting from similar vegetation changes, as observed in large scale, cross-site measurement studies, may help determine whether modelled results are in line with expectations or differ substantially. In the following we relate our results to a few such studies in order to point to possible strengths and weaknesses in model parameterization and configuration.

Changes in albedo are largest in spring and autumn months, reflecting the differences in LAI in these periods. In summer, the broadleaved deciduous species reach their peak LAI values, and the difference to the evergreen needle leaf trees is smallest. In winter, the effect of difference in LAI is at its largest; however its effect on the surface albedo is to a great extent masked by snow cover. The areas of evergreen needle leaf forest expansion has a profound impact on summer- and autumn- months albedo, but interestingly a low impact on modelled albedo during winter months. In fact, the effect of the evergreen forest migration on winter albedo is nearly zero during winter months.

It has been suggested that the lowering of surface albedo over snow covered ground, as result of taller and more complex canopies as compared to snow covered tundra, will greatly affect wintertime surface heat fluxes and that the lower wintertime albedo would also increase snowmelt and prolong growing seasons (e.g. Bonan et al., 1992;Betts and Ball, 1997). However, the parameterization of snow albedo in relation to high latitude vegetation has been pointed out as a source of uncertainty in high latitude climate modelling (e.g. Qu and Hall, 2006;Loranty et al., 2014). Loranty et al. (2014) found that on average the CMIP5 model tree cover and albedo do not correlate well. They also point out that the observed general decreasing albedo with increasing tree cover south of the latitudinal tree line seems badly represented in coupled climate models.

In WRF (Noah), the vegetation-specific surface albedo is weighted against a corresponding vegetation-specific snow albedo value from Robinson and Kukla (1985). A vegetation-dependent threshold value with regard to snow water equivalent (SWE) is used to determine if the ground is fully snow-covered, and for fresh snow, a higher albedo value is estimated to decay towards the fixed vegetation snow albedo values over a period of a few days. This parameterization is based on Koren et al. (1999), after revisions by Livneh et al. (2010). The snow albedo parameterization in WRF-Noah has been subject to a number of studies in recent

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years, some revealing weaknesses related to early snowmelt as a result of too low snow albedo values. However, recent improvements were suggested by Wang et al. (2010), who found that an increase in the snow cover threshold value for high vegetation, and lowering for low vegetation, reduced over (under-) estimation of snow albedo over high (low) vegetation. This alteration, together with other minor improvements, has recently been made available as an option in Noah and Noah-MP (Noah land surface model with multiparameterization options) (Yang et al., 2011;Niu et al., 2011), and as such it would be of interest to test this version in a further study. A verification of estimated snow cover and snow albedo against observations for the simulated study area is beyond the focus of this study, however, the results herein suggest that the rather low wintertime warming seen in the evergreen forest expanding areas, may be somewhat underestimated.

Beringer et al. (2005) examined the potential influence of structural vegetation changes by measuring surface energy exchanges along tundra- to forest transition zone in Alaska during the summer of 1999. They measured sensible heat fluxes and evapotranspiration in five different sites (tundra, low shrub, tall shrub, woodland and forest) acting as an analogue to vegetation transitions that might occur under enhanced warming. Despite the fact that measurement sites in Beringer et al. (2005) and the simulation domain herein differ in both time and continent, comparing the results points to some general features of summer surface energy partitioning related to vegetation changes, and may as such be useful. They reported small differences in latent energy flux between the sites, and a decrease in ground evaporation was compensated by an increase in evapotranspiration moving from tundra towards more complex canopies. Sensible heat flux was ~~greatly~~ increased going from tundra to more complex canopy vegetation, with both shrubs and trees ~~greatly~~ enhancing the sensible heat flux to the atmosphere. ~~Despite the fact that measurement sites in Beringer et al. (2005) and the simulation domain herein differ in both time and continent, comparing the results points to some general features of summer surface energy partitioning related to vegetation changes, and may as such be useful.~~ These findings are supported by modeled findings for heat flux changes resulting from similar vegetation changes (Jeong et al., 2011;Jeong et al., 2014;Snyder and Liess, 2014). Snyder and Liess (2014) found annual mean increases in both sensible and latent heat fluxes as response to lowered albedo and increased net radiative forcing. For the summer months, the increased radiative flux was partitioned into sensible rather than latent heat, due to re-partitioning of evaporative flux, leading to a JJA temperature increase of 0.4 K, and little or no increase in near surface humidity and precipitation. Jeong et al. (2014) on the other hand, found increases in both latent and sensible summer season fluxes in response to arctic greening, leading to relatively large increases in JJA near surface temperatures (1.95 K).

~~Measured differences in sensible heat fluxes between vegetation types~~These results~~,~~ stand in contrast to our simulated sensible heat flux~~es~~, which is~~are~~ reduced in summertime as result of tree- and shrub expansion into previously tundra covered regions. In areas with changing tundra (from mixed tundra to wooded tundra), the largest monthly mean effect is seen in June, with an average reduction of sensible heat of 1.3 W m^{-2}, and in areas with northward expanding evergreen forest the main effect is seen in July, with a mean reduction of the sensible heat flux by 11.2 W m^{-2}.~~ (Jeong et al., 2011;Jeong et al., 2014;Snyder and Liess, 2014)The discrepancy in sensible and latent heat flux response points out some important features of the model parameterization.~~ ~~ ~~The simulated sensible heat flux is closely related to wind speed, and in~~. In~~ areas where wind speeds are lowered, the ~~sensible~~turbulent heat fluxes decrease~~.~~. Furthermore, the increase in available soil moisture (by increased rooting layers) going from tundra to evergreen forest acts to increase the transpiration and thereby the latent heat flux. Also, increased leaf area and corresponding inception and canopy evaporation serves to increase the latent heat flux and near surface humidity, resulting in increased summer precipitation. An analysis of the mean JJA rainfall in this area alone shows an increase in accumulated rainfall of 3,35% over the ten summers. Increased rainfall would further increase the partitioning of increased absorbed radiation into latent rather than sensible heat flux, and thereby decrese heating of the overlying atmosphere. This flux re- partitioning leads to an annual 2 m temperature increase of 0.12 ^{o}C in areas with evergreen forest expansion.

~~At the same time, a decrease in surface heat flux results in lower summer-time 2 m temperatures and boundary layer height.~~

The specifics of vegetation perturbations applied here might have influenced these results. Here, we have chosen to only perturb the vegetation type in each area. The greenness fraction is not altered, which influences the evapotranspiration and thereby available energy for sensible heat, as demonstrated by (Hong et al., 2009). Here, we concidered this approach sufficient, as the greenness fraction acts to scale the LAI (and other vegetation parameters) values within the vegetation specific range (as indicated in the plotted results for the variable), applying the new vegetation category to new areas would not imply a scaling of the LAI to values outside the respective category's assigned range. Further investigation of the

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sensitivity of these parameters is beyond the scope of this study, but certainly important subjects for further work.

Based on a broad analysis of available observational data from arctic and boreal ecosystems, Eugster et al. (2000) found a general increase in latent heat flux in areas with deciduous trees replacing evergreen needle leaf forest, due to lower canopy conductance in conifer trees. A similar, yet less drastic replacement was made in our Ex 2, where replacement of evergreen needle leaf forest by mixed forest (representing a mix of conifer and deciduous trees. This shift in vegetation causes a modelled year-round reduction in latent heat. This is a result of the model parameterization, which causes a decrease in LAI, but no increase in stomatal conductance given the vegetation shift in Ex 2, and thereby acts to decrease the latent heat release to the atmosphere. Our experiments suggest a significant increase in latent heat flux in summer months in areas with evergreen forest expansion.

Based on summer season observations of flux partitioning over 66 site years within the FLUXNET project (Baldocchi et al., 2001), Wilson et al. (2002) found that deciduous forest sites in general had a lower summer Bowen ratio (~0.25-0.5) than conifer forest sites (~0.5-1.0), which again were slightly lower than tundra Bowen ratios. In our simulations, areas with a northward migrating evergreen forest (northern border) reduce the summer season (JJA) Bowen ratio by a factor two, going from wooded tundra to evergreen forest. In areas of northward migrating mixed forest (southern boarder), the decrease in both sensible and latent heat fluxes results in a slightly decreasing Bowen ratio from 0.51 to 0.49.

The modelled increase in evapotranspiration in areas of northward migrating evergreen forest also affect the soil moisture, with more water being extracted from especially the deeper layers of soil, owing to the increased number of available soil layers by evergreen forest. However, the latent heat flux is not highly correlated to the soil moisture content in this domain, as fluxes are largely energy limited rather than moisture limited. Shifting the vegetation type towards higher LAI vegetation, acts to reduce correlations for summer months between latent heat and soil moisture, and increase correlations with VPD. These results are in agreement with the findings of ~~e.g.~~ Kasurinen et al. (2014), who measured latent heat fluxes over a total 65 different boreal and arctic sites. They found a general increase in latent heat release and a higher correlation to VPD in observations from forested boreal sites, compared to tundra ecosystems.

5 Concluding remarks

In this study, observed trends of boreal forest migration were represented by applying perturbations to the current boreal vegetation distribution in two separate experiments. The perturbations were simple enough to extract their separate effects on the overlying atmosphere, and moderate enough that they induce realistic and relevant information on atmospheric response to vegetation structural changes.

The atmospheric response resulting from the vegetation changes made in Ex 1 and Ex 2 largely points in different directions. The Ex 1 high north shrub- and evergreen forest expansion largely leads to a decreasing albedo and larger latent heat fluxes, which subsequently lead to enhanced near surface temperatures and deeper and wetter planetary boundary layer. Increased summer precipitation and ~~R~~reduced wind speed leads to lower sensible heat flux, causing a lowering of the Bowen ratio changing from tundra to conifer forest. On the other hand, the Ex 2 replacement of evergreen forest by more broadleaved species along the southern border of the boreal forest, leads to lower LAI, higher albedo and lower surface fluxes, resulting in lower heating of the boundary layer and lower near surface temperatures and humidity. The differing response of the various vegetation changes results in that the overall effect on the domain is a near zero temperature response on a 10 year average. However, there are large seasonal differences in atmospheric response for the individual vegetation shifts.

The study has been successful in uncovering some special features of model parameterization that might yield unexpected results relative to physical observations of vegetation changes, such as the masking of albedo changes by snow cover, reducing the expected warming in winter and spring, and the lowering instead of increase in sensible heat for more complex canopies. Although latent heat and soil moisture content are closely linked variables, the low correlations found between the two prove that the high latitude study domain is energy, rather than water- limited throughout the year.

In our simulations the perturbations are kept moderate enough to be achieved within this century, and although a result of large climatic average changes in the area, the mean response of the present day atmosphere is not regarded very different from what can be expected as feedbacks from the one accompanying such vegetation changes. We have mainly focused on long term average effects and seasonal mean variations. Many feedback processes are not possible to study in this time resolution, and shorter, more specific time periods might be advantageous in this respect. For the purpose of more detailed investigation on finer temporal and spatial scale, future work include the use of these long term simulations as framework for nested, finer resolution simulations, focusing on more specific processes in vegetation atmosphere feedbacks.~~ This study will to that end act as a screening of long term, large feature effects, and as downscaling of boundary conditions for more detailed perturbations and possibly tests of alternative parameterizations in the next, finer scale study.~~

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~~Table 1. Key parameterizations chosen for the model setup.~~Table 1. Key parameterizations chosen for the model setup.

Parameterization scheme	Reference
Mellor-Yamada-Janjic planetary boundary layer	(Janjić, 1994)
Morrison two moment microphysics	(Morrison et al., 2009)
RRTMG short- and long wave radiation options	(Iacono et al., 2008)
Kain–Fritsch cumulus scheme	(Kain, 2004)

~~Table 21. Key parameters for the dominant vegetation categories used in Ex 1 and Ex 2.~~Table 2. Key parameters for the dominant vegetation categories used in Ex 1 and Ex 2.

Vegetation category	Min LAI	Max LAI	Roughness length	Min albedo	Max albedo	Rs	Max snow albedo
Mixed Tundra	0.41	3.35	0.15	0.15	0.2	150	60
Wooded tundra	0.41	3.35	0.3	0.15	0.2	150	55
Evergreen needle leaf forest	5	6.4	0.5	0.12	0.12	125	52
Mixed forest	2.8	5.5	0.5	0.17	0.25	125	53

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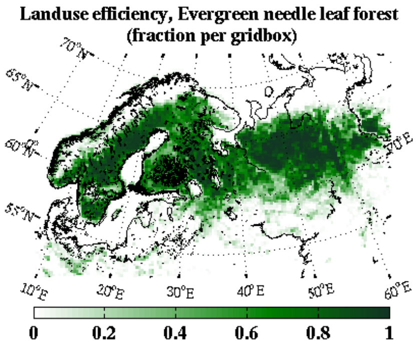


Figure 1. The northern European boreal forest domain, represented here by evergreen needle leaf forest as fraction of grid cell, remapped from the modified IGBP MODIS data to 27x27 km resolution.

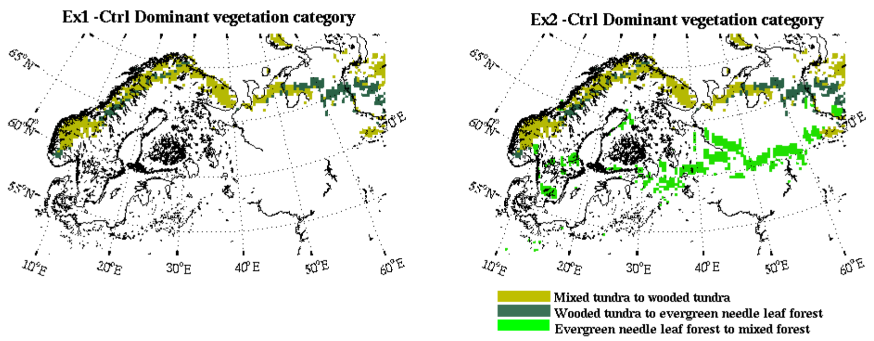


Figure 2. Changes in dominant vegetation category as compared to control simulation for Ex 1 (left panel) and Ex 2 (right panel). Beige color represents areas where the dominant category is changed from mixed tundra to wooded tundra to represent shrub expansion. Dark green color indicates areas where the dominant land use category of wooded tundra has been replaced by evergreen needle leaf forest. Light green color represents areas where mixed forest has taken over for evergreen needle leaf forest (only Ex 2).

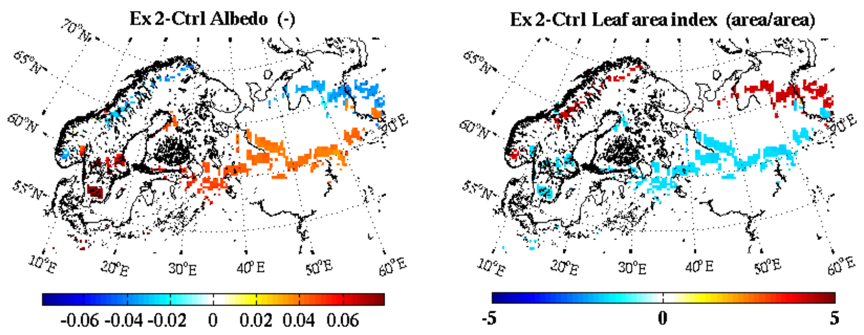


Figure 3. Changes in 10 year average albedo (left panel) and LAI (right panel) for Ex 2 (including all vegetation changes), as compared to control simulation.

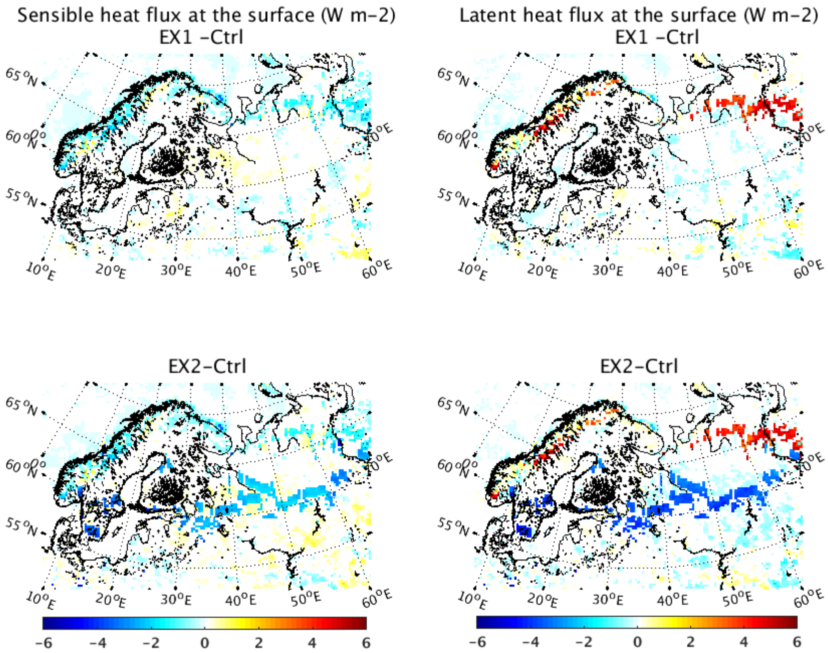
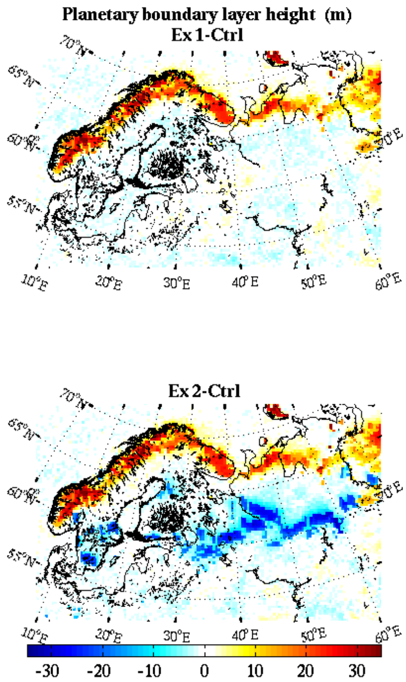


Figure 4. Changes in 10 year average surface sensible heat flux (left panels) and latent heat flux (right panels), as compared to control simulation. Ex 1 in upper panels, Ex 2 in lower panels (Only showing significant results at the 95% confidence level).



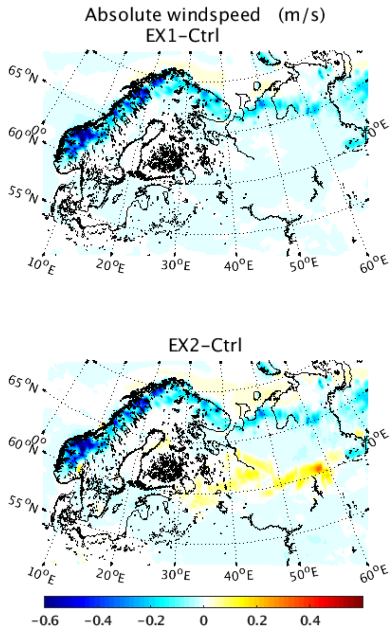


Figure 5. Changes in 10 year average absolute wind speed (m/s) for Ex 1 (upper panel) and Ex 2 (lower panel) as compared to control run.

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~~Figure 5. Changes in 10 year average planetary boundary layer height as compared to control simulation. Ex 1 changes in upper panel, Ex 2 in lower panel.~~

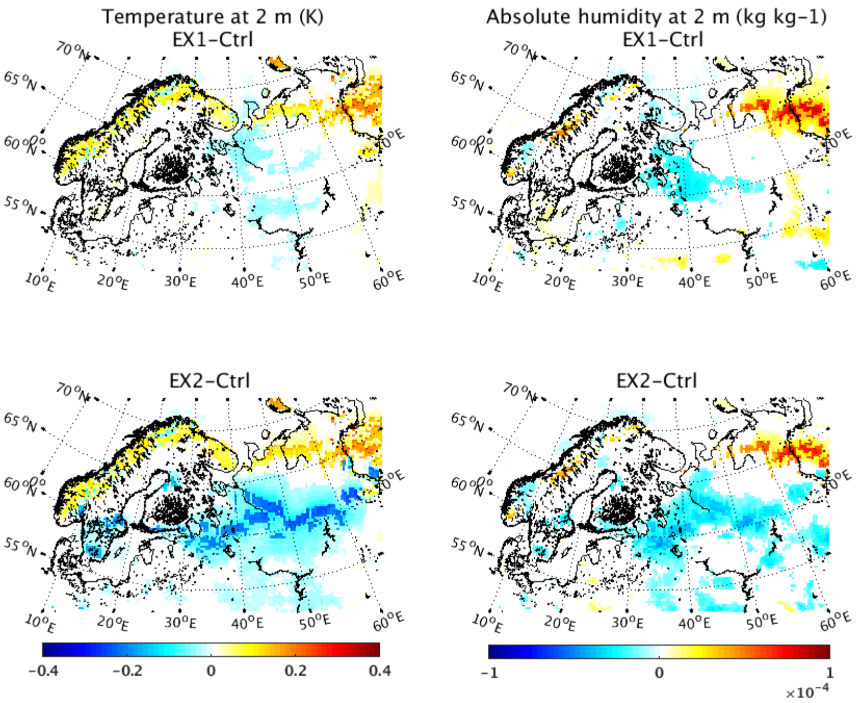

Figure ~~6~~6. Changes in 10 year average near-surface variables as compared to control run. 2 m temperature change (left panels) and ~~percentage~~ change in 2 m absolute humidity (right panels). Ex 1 in upper panels, Ex 2 in lower panels, (Only showing significant results at the 95% confidence level)..

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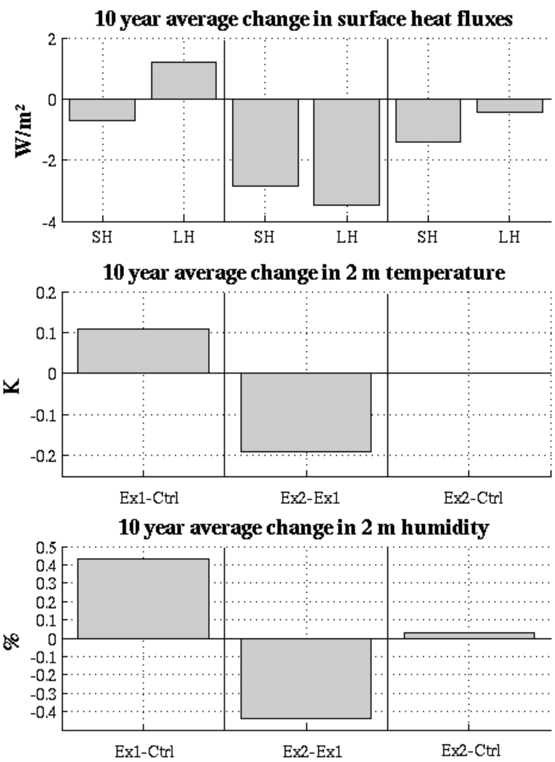

Figure ~~7~~7. Changes in 10 year averages in surface variables, as averages per area of vegetation change only. Left side bar(s) shows vegetation shift effects of Ex 1 compared to control run (northward migration of evergreen forest and shrub expansion combined). Middle bar(s) shows effect of mixed forest migration only, given as difference between Ex 2 and Ex 1. Right bar(s) show the effect of all vegetation changes together, averaged over all areas with vegetation changes. Note that areas of different vegetation shifts are not equal in size, and therefore averages are not additive.

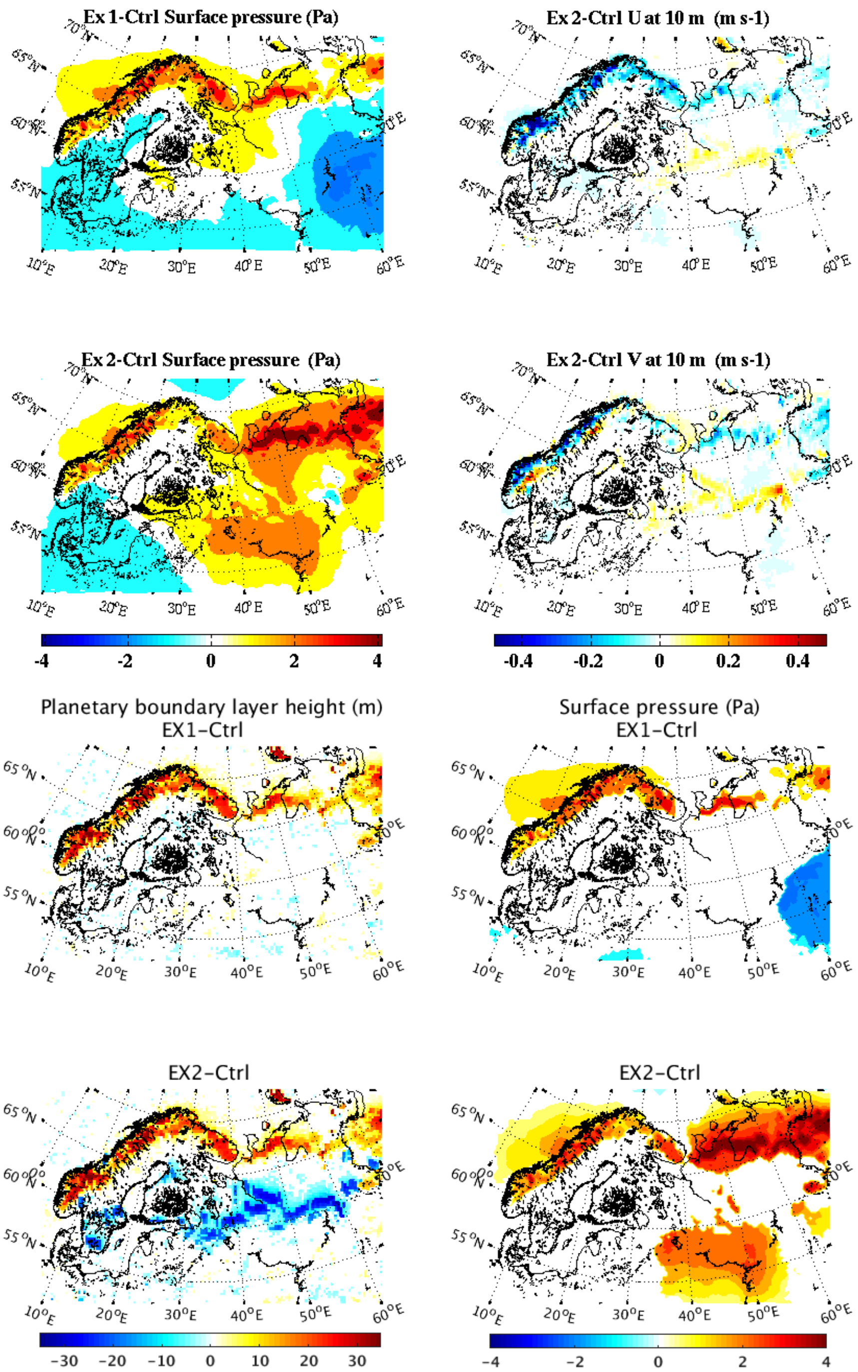

Figure ~~8~~8. Changes in 10 year average planetary boundary layer height (left panels) and surface pressure (right panels) for Ex1 (upper) and Ex2 (lower) compared to control run (only

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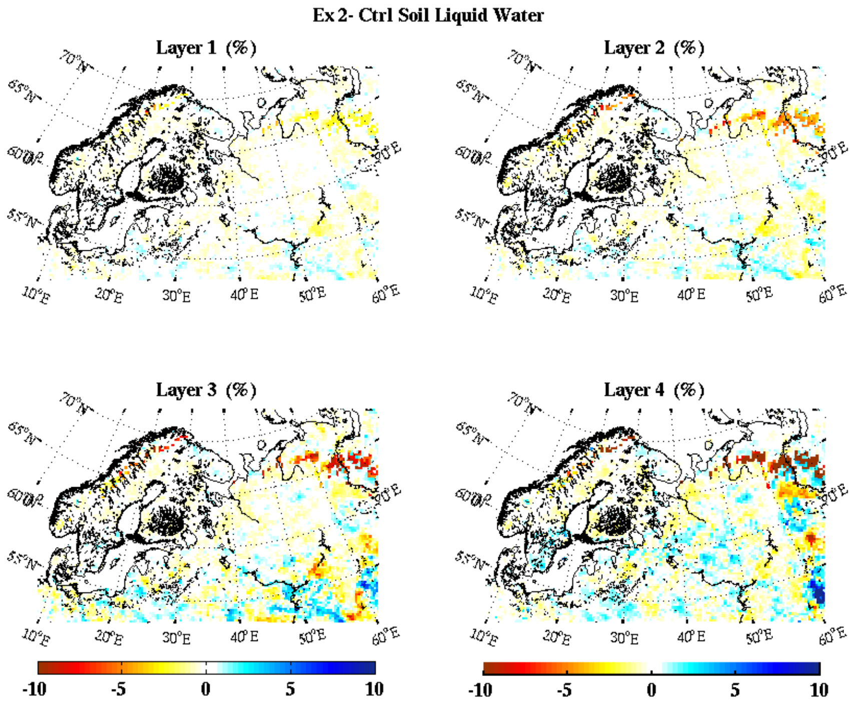
showing results significant at the 95% confidence level).~~ (left panels), and mean eastward wind U (upper right panel) and northward wind V (bottom right panel) for Ex 2 compared to control run. The two wind panels share colorbar.~~


Ex 2- Ctrl Soil Liquid Water
Layer 1 (%)
Layer 2 (%)
Layer 3 (%)
Layer 4 (%)
70°N
65°N
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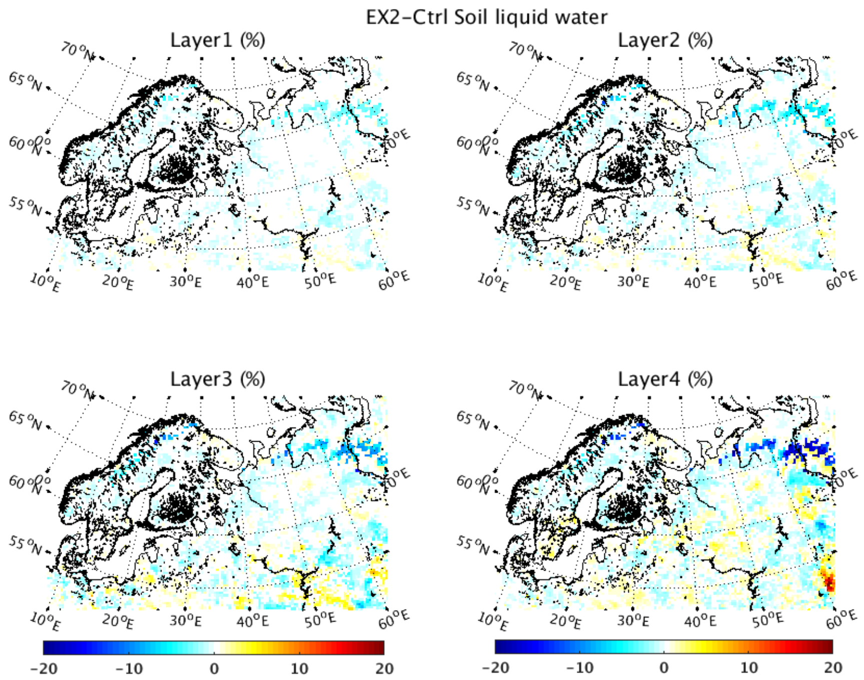
-10
-5
0
5
10


EX2-Ctrl Soil liquid water
Layer1 (%)
Layer2 (%)
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Layer4 (%)
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55°N
10°E
20°E
30°E
40°E
50°E
60°E
-20
-10
0
10
20

Figure ~~9~~9. Percentage change in 10 year average volumetric liquid water soil content for each soil layer, as the difference between Ex 2 and the control run. Note that red colors indicate dryer-, and blue wetter conditions as compared to control run (Only showing significant results at the 95% confidence level).

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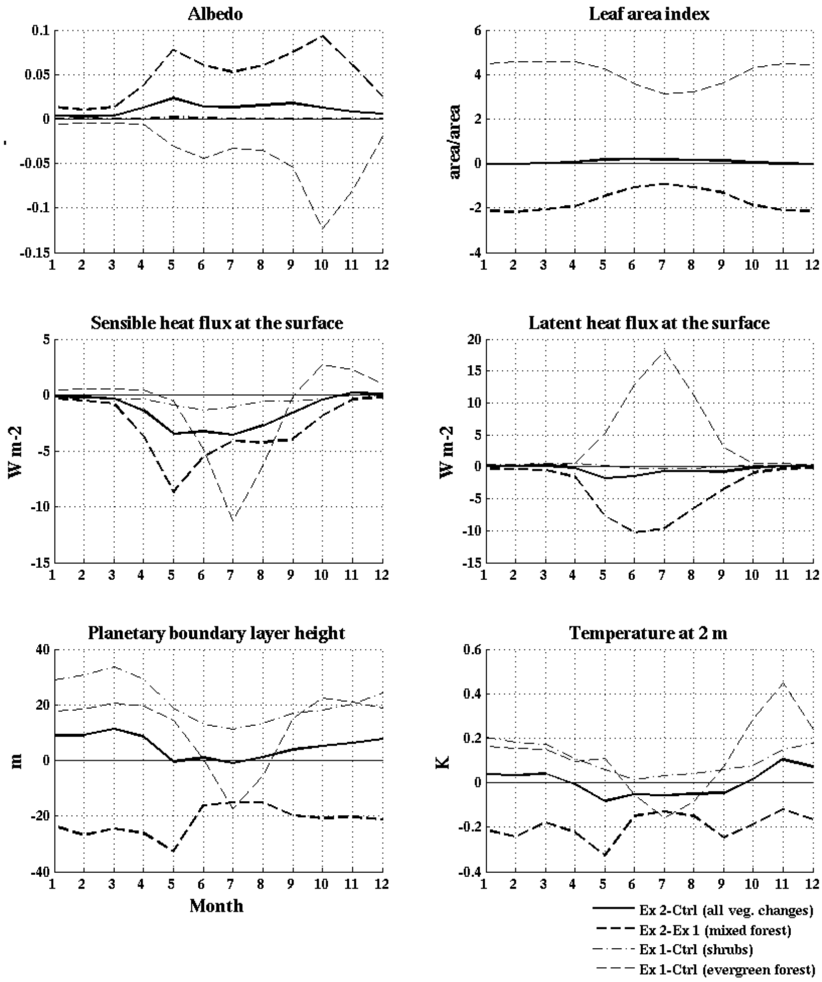

Albedo
Leaf area index
area/area
Sensible heat flux at the surface
W m-2
Latent heat flux at the surface
W m-2
Planetary boundary layer height
m
Month
Temperature at 2 m
K
Ex 2-Ctrl (all veg. changes)
Ex 2-Ex 1 (mixed forest)
Ex 1-Ctrl (shrubs)
Ex 1-Ctrl (evergreen forest)

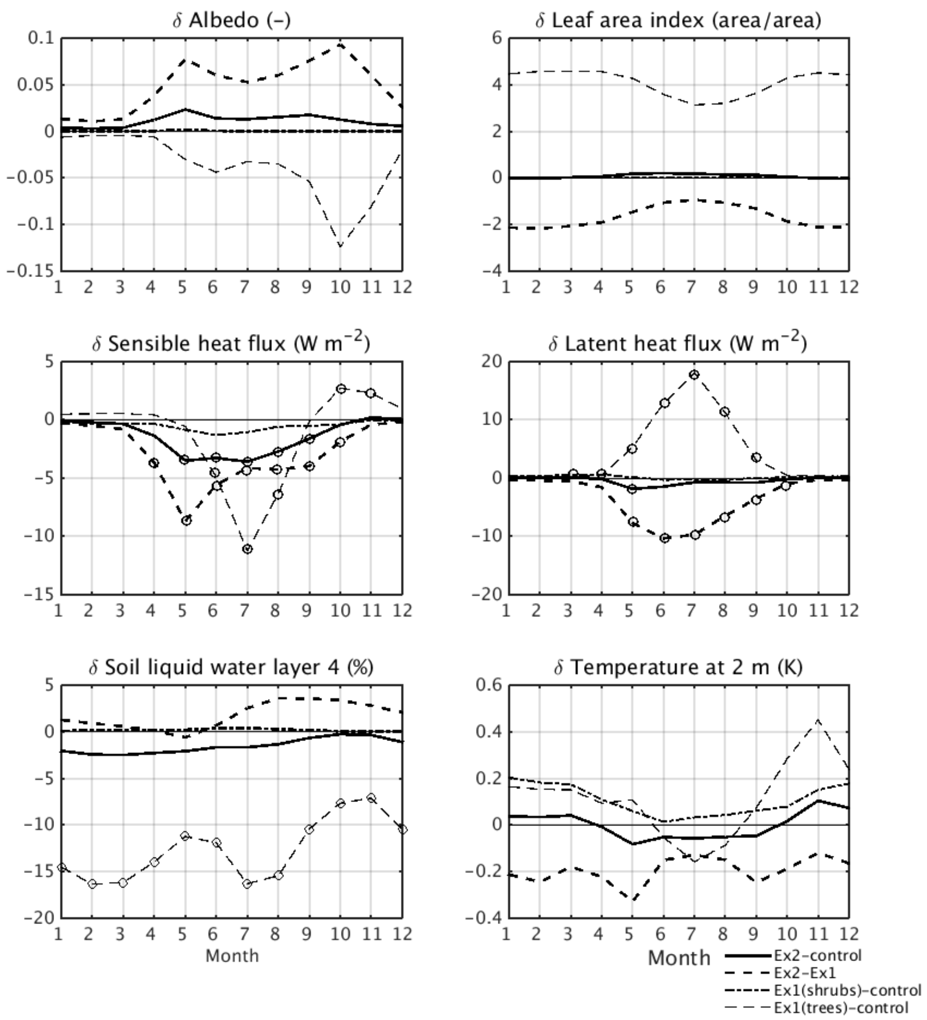

Figure ~~10~~10. Seasonal changes in 10 year monthly average surface- and near-surface variables for each area with changed vegetation. Average of all vegetation changes shown in thick, black line (Ex 2 –Ctrl), black circles indicate significant results at the 95% confidence level.

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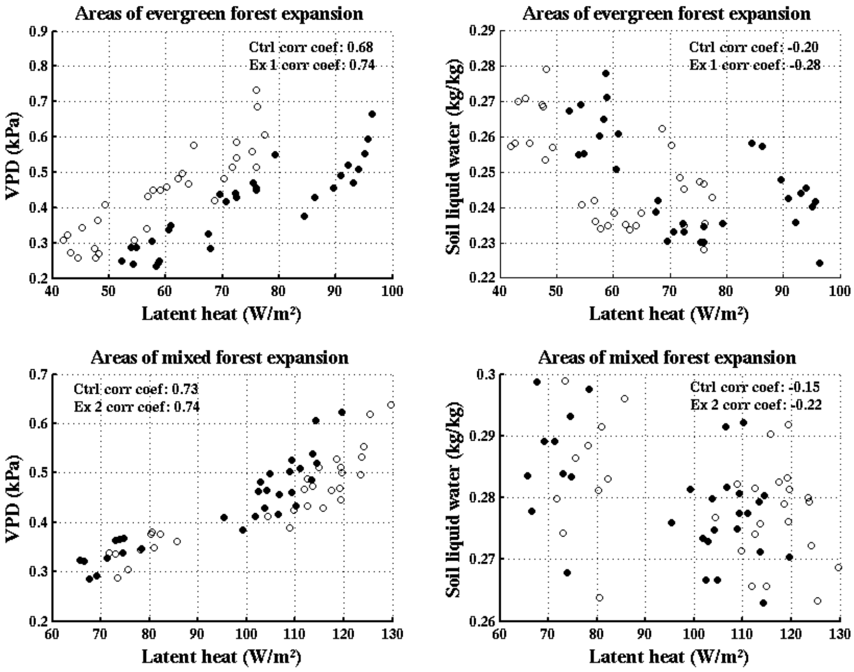

Figure ~~11~~11. Effect of change in vegetation cover on the relationship between the monthly mean latent heat flux and VPD at 2 m (left panels), and latent heat and liquid soil moisture content in the top soil layer (right panels). The data are based on summer season (JJA) monthly means, averaged over areas with northward expanding evergreen forest (upper panels) and areas with northward migrating mixed forest (bottom panels).

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